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SUBSURFACE STRATIGRAPHIC ARCHITECTURE OF PLEISTOCENE SEDIMENTS IN THE GREATER NEW ORLEANS AREA

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Geology and Geophysics

by
James E. Ayrer IV
B.S., Pennsylvania State University, 2010
August 2013

ACKNOWLEDGMENTS

I would like to thank my major advisor, Carol Wicks and my thesis committee members, Jeffrey Hanor and Frank Tsai for their assistance in completing this project. I would like to thank Carol Wicks for her contribution to this research for which she will be a coauthor on when this manuscript is submitted for publication to GCAGS-Transactions. I would also like to thank the USGS Louisiana Water Science Center and Louisiana Department of Natural Resources for making available geophysical well log data and pumping well screen data. John Lovelace and Jason Griffith were also very helpful for insight into Louisiana geology and log interpretation. I would also like to give special thanks to my fiancé, Jessi, for providing constant support.

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ABSTRACT

A major environmental and economic problem currently faces the New Orleans area, in southeastern Louisiana, stemming from salinization of freshwater aquifers that are important resources for the community. Major pumping of these aquifers has altered the potentiometric flow, allowing saltier bodies of water to flow into the region. The impact of pumping wells on encroachment of saltwater and the time as well as the route for saltwater to travel from the current saltwater-freshwater interface to pumping centers is not well constrained. Water planners need additional information to make decisions about future management of groundwater resources. The most effective way to analyze pumping effects on groundwater is to build a computer simulated flow model. However, such a model is reliable only if the permeability pathways and structures through which the water moves are well understood, which necessitates a clear picture of the subsurface geology.

The lithology and structure of the New Orleans subsurface is controlled by the fluvial/deltaic environment that has characterized southeastern Louisiana during the Pleistocene and Holocene periods. The Mississippi River and associated deltas have migrated throughout southern Louisiana over geologic time. The river channels and deltaic lobes that migrate back and forth likely do not return to the exact same spatial coordinates upon return to southeastern Louisiana, creating complications in defining stratigraphic features. Therefore, a geologic model was produced using well log correlation to characterize both lateral continuity and thickness of lithologic units. The geologic model and associated cross sections highlight proposed locations of geologic units only when the units are clearly indicated in geophysical logs. Results reveal a highly heterogeneous subsurface, where units are discontinuous at scales of 1000 ft (300 m), highlighting the significant lack of available geophysical logs to create an accurate geologic

model. Therefore, many plausible realizations of the subsurface architecture are possible, and variability of factors used for lithologic correlation can create large differences in the numerical modeling of saltwater encroachment, demonstrating a need to explore new stochastic methods of correlation in complex environments such as the New Orleans area.

1. INTRODUCTION

Salinization of coastal aquifers is a problem that faces many communities. In southern Louisiana, multiple aquifers are impacted by salinization, including those of the New Orleans area (Dial and Sumner, 1989; Tomaszewski, 2003; Stoessell and Prochaska, 2005; Prakken, 2009). In general, there are several sources of saline water to coastal aquifers. In the New Orleans area, saltwater is thought to move up a series of fault planes, and then is transported laterally within the aquifer units due to groundwater withdrawal (Stoessell and Prochaska, 2005). The New Orleans area (Fig. 1) consists of multiple parishes, including portions of Orleans, Jefferson, St. Bernard, St. Charles and Plaquemines parishes. The New Orleans area has historically used Mississippi River water for public supply, while groundwater has been used for industry, power supply and irrigation. However, even without the added stress of public supply, groundwater withdrawal in the region has altered the hydraulic gradient, creating a situation favorable for saltwater intrusion (Dial and Sumner, 1989; Prakken, 2009).

One of the key questions facing the water planners and managers of the New Orleans area is the degree to which groundwater withdrawal affects saltwater encroachment in terms of the time and route for saltwater to travel from the current saltwater-freshwater interface (Fig. 2) to pumping centers. Water planners need additional information to help make decisions about the future management of groundwater resources in the New Orleans area. Therefore, further study is necessary to provide a better understanding of the hydrologic system and to assess the effects of potential saltwater intrusion mitigation strategies in the New Orleans area.

There are scenarios that create a need to evaluate groundwater resources, such as times when the current water resources are not available. Strong storms can cause power outages and damage to water distribution facilities. This occurred in 2005, when Hurricane Katrina caused

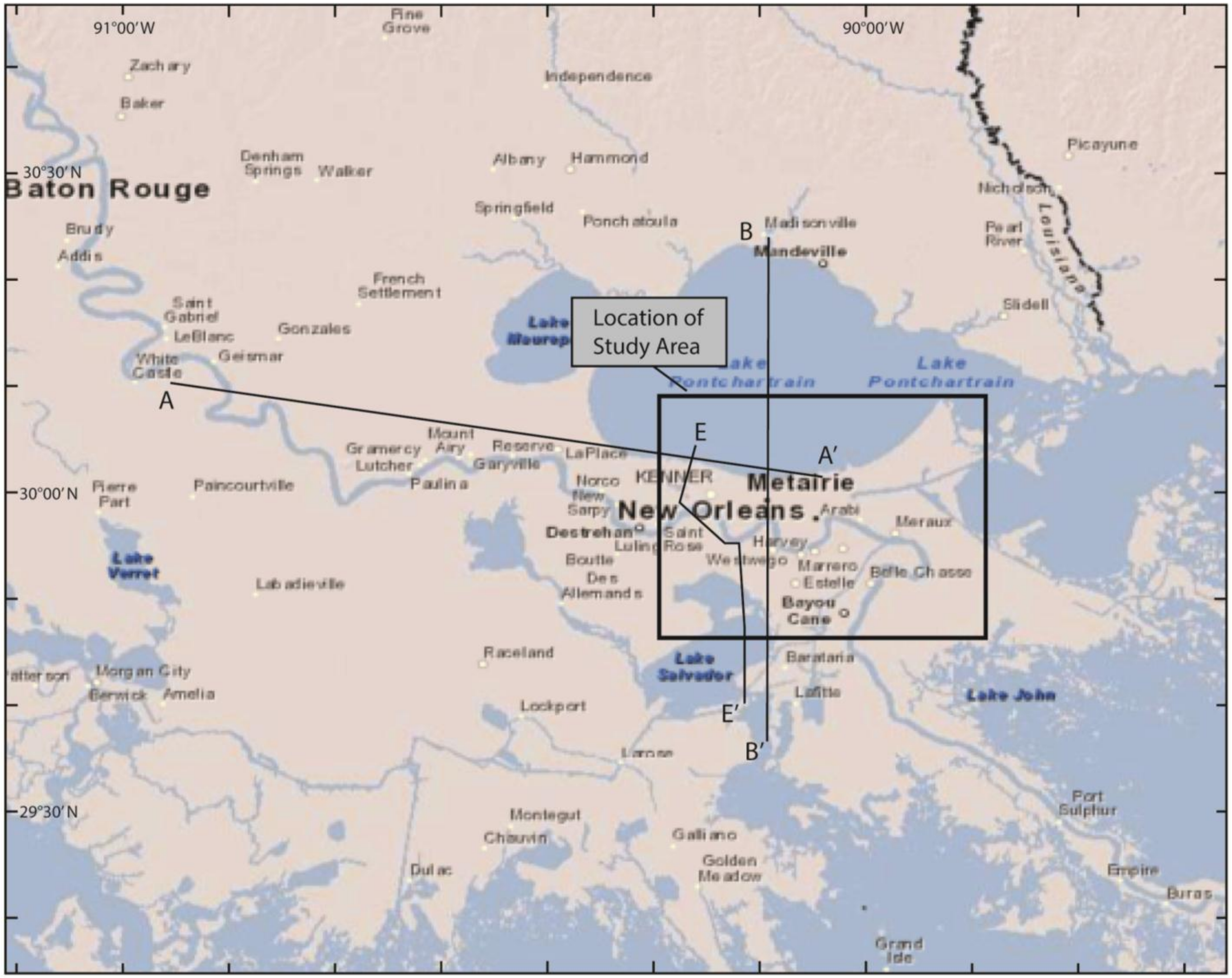

Figure 1. Map of southeastern Louisiana that shows the locations of modified cross sections from Dial and Sumner (1989) and McFarlan and LeRoy (1988). Map also highlights the location of the study area.

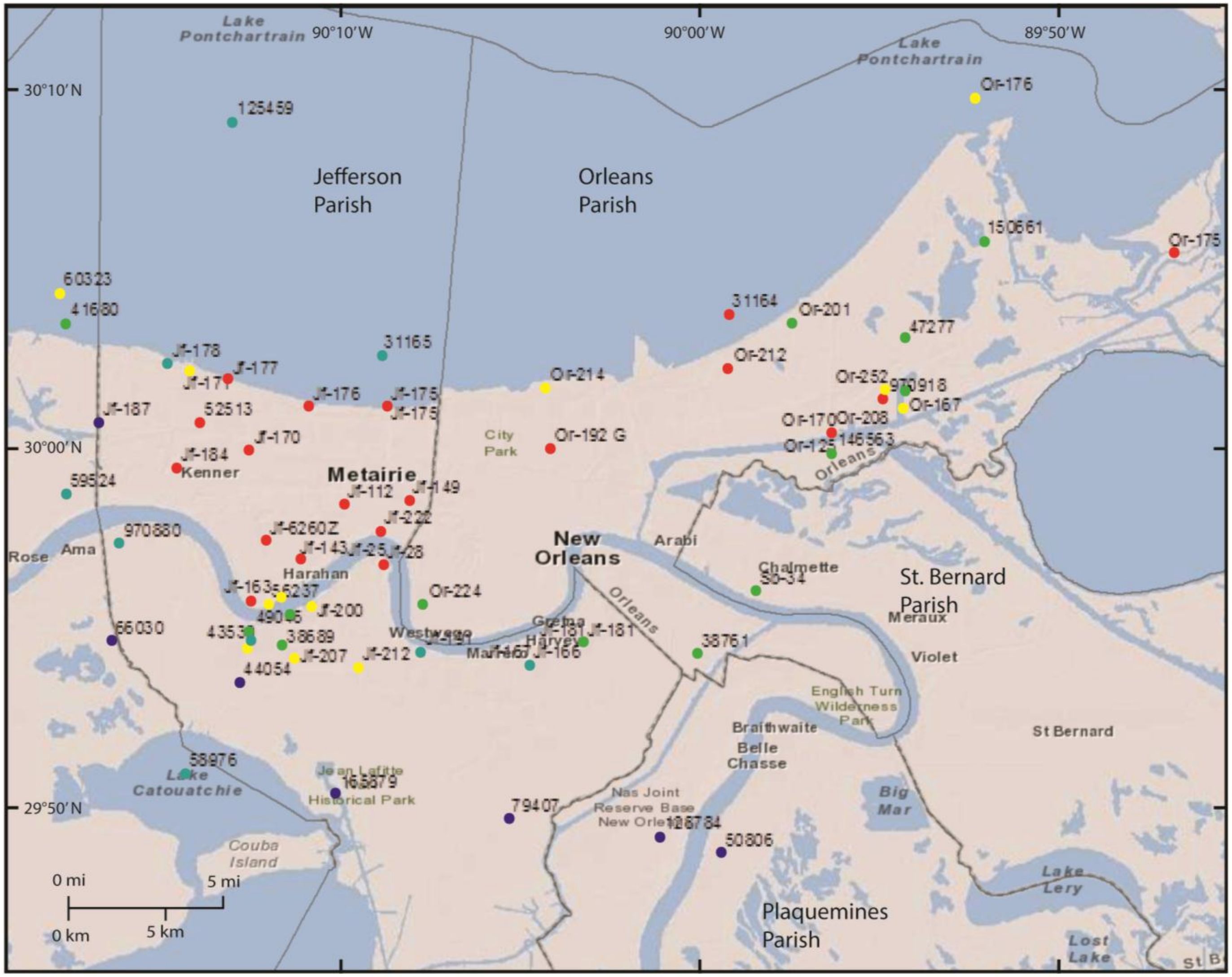

Figure 2. Map showing chloride concentrations from sampled observation wells (Prakken, 2009) and from geophysical well log analysis. Red wells contain water having chloride concentrations less than 250 mg/L. Yellow = 250 mg/L – 500 mg/L. Green = 500 mg/L – 1000 mg/L. Turquoise = 1000 mg/L – 2000 mg/L. Blue = 2000 mg/L – 4000 mg/L.

damage to water supply facilities, including power outages, flooding of treatment facilities and damage to the water distribution lines (Black and Veatch Corporation; 2008). Dial and Tomaszewski (1988) discussed deteriorating water quality as another cause for concern. New Orleans is located near the mouth of the Mississippi River, which is approximately 2,320 miles in length. Such a large span creates many opportunities for hazardous spills of chemicals. Smith and Hanor (1977) documented several threats that occurred in 1974 due to two crude oil spills. Kazmann and Arguello (1973) determined that if river flow is low enough (150,000 cubic feet per second), saltwater from the Gulf of Mexico can move upstream into positions of water intake. These reasons can impact the quality of surface water for public drinking use and can create a need to switch to a different source of drinking water, such as groundwater. However, the main concern that prevents a large use of groundwater in the New Orleans area is the presence of saltwater in the aquifers. Presently, the saltwater-freshwater interface is located mainly to the south of the Mississippi River, but increased groundwater withdrawal can shift the location of the interface.

Dial and Sumner (1989) calculated saltwater-freshwater interface velocity towards the Industrial Canal region at 150 feet/year when 1980 pumping rates were extrapolated into the future from 1989 to the year 2006. The effects of density and dispersion were not incorporated into this calculation. In 1987, the interface was roughly 15 miles from the major pumping centers. At this rate, the interface would not reach the center of pumping for 500 years. However, Dial and Sumner (1989) also ran another scenario with groundwater withdrawal increased from 40 MGal/day to 170 MGal/day. This increased groundwater withdrawal rate was meant to capture the estimated needs for public supply to rely solely on groundwater. The increased rates indicated that the rate of saltwater encroachment increased to 500 feet/day.

Therefore, if the pumping rates were increased, only about 100 years was needed before the interface reaches the pumping centers. However, these rates likely no longer apply due to a shift in major pumping locations through time. No other studies have attempted to model fluid flow in the New Orleans area since 1989, and solute transport and density effects have never been incorporated in any modeling study of this region.

Computing power has advanced exponentially since the time of the Dial and Sumner study, enabling much faster, and therefore more detailed, simulations. Dial and Sumner (1989) used a grid cell size of one square mile in horizontal extent in the detailed section of the grid. At the time, the size of the model area required large grid cells. These large cells are not effective at capturing the heterogeneity existing in the subsurface. Multiple density fluid flow and solute transport computer codes became more developed in the late 1990s and early 2000s, enabling more precision to the saltwater encroachment issue.

While a computer flow simulation model is necessary in order to evaluate groundwater management, such a model must be based on an accurate subsurface architecture that captures the permeability pathways through which the water moves. The current geologic representation of the subsurface does not have the resolution to capture the heterogeneity that exists. Therefore, a more refined geologic model is in need of development before further studies can commence. The goal of this study is to create an accurate view of the geology of the region, to determine the scale of heterogeneity and to evaluate how changes in architecture due to variables such as dip can have direct impact on groundwater flow and solute transport. In order to accomplish the work, lithologic cross sections were developed using well log correlation at different spatial scales tied with groundwater withdrawal well screens to characterize the lateral connectivity and thickness of stratigraphic units.

2. STUDY AREA

2.1 Regional Geology

Coastal Louisiana can be divided into two main segments. The southeast, the focus area of this study, is known as the deltaic plain of the Mississippi River. The region is bounded on the north by older, gulfward dipping Pleistocene deposits (Kolb and Van Lopik, 1966). The northern portion of the deltaic plain is considered to be the New Orleans area, where natural levees are present along the Mississippi River. Pleistocene deposits are found at an average depth of 80 feet below New Orleans, and rise to the north to form a coastal terrace (Kolb and Van Lopik, 1966). These young Pleistocene deposits were present at the surface at the time of the last glacial advance (Late Wisconsin), and have subsequently been buried in the last 20,000 years. Currently, beaches of southern Louisiana compose the southern border of the deltaic plain.

The deltaic plain is so named due to the overlapping sequences of deltaic formations, which have characterized southeastern Louisiana during the Pleistocene and Holocene. Each depositional cycle contains a coarse substratum capped by a fine top-stratum, relating to different stages of sea level (McFarlan and LeRoy, 1988). Continental glaciation and corresponding sea level changes were important forcing mechanisms for Gulf of Mexico stratigraphy (Coleman and Roberts, 1988; Blum and Tornqvist, 2000). At low stand, river systems advanced to the shelf edge and upper slope and constructed low-stand deltas. During the Wisconsin glacial period (20,000 years ago), sea level was 400 feet (150 m) below present levels (Kolb and Van Lopik, 1966). Once the glacial maximum had ceased, sea level began to rise, greatly decreasing the energy of the ancestral rivers and causing mass alluviation of the coarse sands and gravels. As sea level rose, depositional environments retreated landward by approximately 100 miles (160 km) (Dial and Kilburn, 1980; McFarlan and LeRoy, 1988; Galloway, 2001). As sea level continued to rise, the alluviation progressed upstream, and allowed clays and silts to cover the previously deposited sands and gravels. This trend continued until sea level rise was stabilized, around 7,500 years ago, at which point modern deltas formed and caused subsequent avulsions to new river channels (Kolb and Van Lopik, 1966; Frazier, 1967; Fisher 1969). There are several deltaic complexes (Fig. 3) that have formed in the last 7500 years that each reflect a route change of the Mississippi (Coleman, 1964; Kolb and Van Lopik, 1966). These include the Sale-Cypremort, Cocodrie, Teche, St. Bernard, Lafourche, Plaquemines and Balize. Knowledge of current Mississippi River fluvial/deltaic deposition can be used as a reasonable analog to help interpret patterns of older sediments deposited in a similar environment. Stratigraphic units analyzed in this study include both the New Orleans Aquifer System as well as deeper sand bodies identified by McFarlan and LeRoy (1988) to be Pleistocene in age based on a series of index fossils.

2.2 The New Orleans Aquifer System

The New Orleans Aquifer System is composed of six aquifers that include Mississippi River point-bar deposits, the shallow aquifers of the New Orleans area, Gramercy, Norco, Gonzales-New Orleans and the ‘1200’ foot sand (Tomaszewski, 2003; Prakken, 2009). The New Orleans area aquifers are composed of alternating beds of sands (aquifers) and clays (confining layers) that dip and thicken southward, shown in Figure 4 (Dial and Sumner, 1989; Tomaszewski, 2003). Relevant aquifers to this study are of Pleistocene (New Orleans Aquifer System) and Holocene (Shallow Aquifers) age (Table 1). Dial and Tomaszewski (1988) determined that each of the aquifers in the New Orleans system has varying amounts of saltwater present.

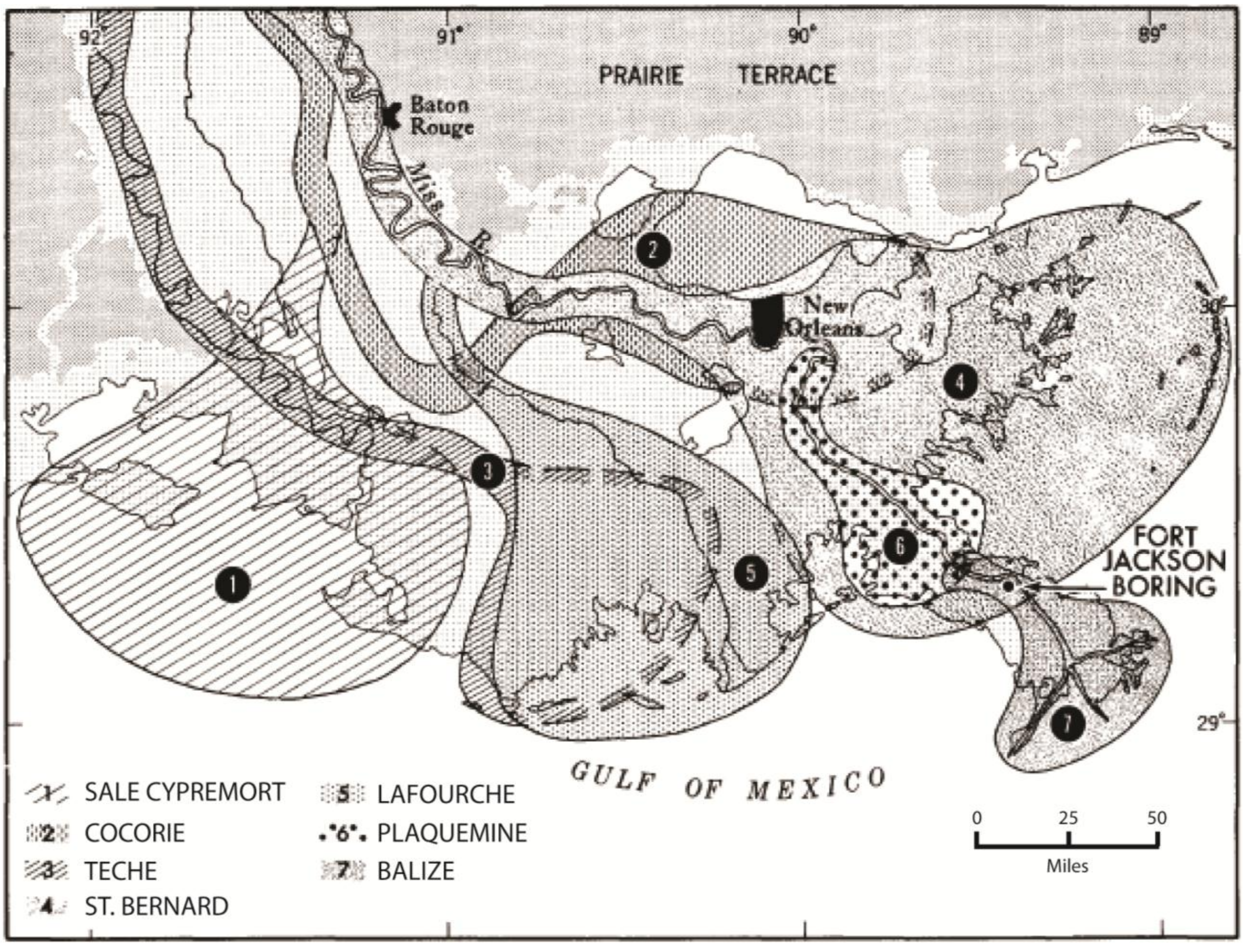

Figure 3. Approximate locations of Mississippi River deltas during the current interglacial period (Modified from Coleman, 1964).

In 2005, these aquifers supplied 20.5 million gallons per day to the New Orleans area for use in industry, irrigation, and power generation (Prakken, 2009). The pumping in 2005 represents a continuing trend in the area of decreased pumping since its high point of approximately 60 million gallons per day in 1970 (Fig. 5). Groundwater pumping rates in Jefferson Parish have been fairly consistent at about 10 MGal/day, meaning the majority of the pumping decrease since 1970 was from Orleans Parish. The Gonzales-New Orleans aquifer is the most developed, defined in terms of groundwater withdrawal, of the aquifers in the system. Historic groundwater flow follows a path from the northern exposed outcrop areas (northern shore of Lake Pontchartrain, Tangipahoa and St. Tammany parishes) southward towards discharge into the Mississippi River Alluvial Aquifer (Dial and Tomaszewski, 1988). Faulting has not been determined to have an appreciable impact on groundwater flow, and is not thought to offset the stratigraphy significantly (Dial and Sumner, 1989). Pumping is causing a significant water level decrease and it is clear that the flow directions have altered towards major pumping centers (Fig. 6).

Table 1. Hydrogeologic units in the New Orleans area separated by aquifer system and age (modified from Griffith, 2003). Note that important units for the purpose of this study are Pleistocene in age.

<table>
<tr><th>System</th><th>Series</th><th colspan="3">Aquifer or Aquifer System
(clay units separating aquifers are unnamed)</th></tr>
<tr><td rowspan="6">Quaternary</td><td rowspan="2">Holocene</td><td rowspan="6">New Orleans Area Aquifer System</td><td rowspan="2">Shallow Sand Aquifer System</td><td>Point-bar Deposits</td></tr>
<tr><td>Shallow Aquifers of the New Orleans Area</td></tr>
<tr><td rowspan="4">Pleistocene</td><td colspan="2">Gramercy Aquifer</td></tr>
<tr><td colspan="2">Norco Aquifer</td></tr>
<tr><td colspan="2">Gonzales-New Orleans Aquifer</td></tr>
<tr><td colspan="2">“1,200-foot” Sand Aquifer</td></tr>
</table>

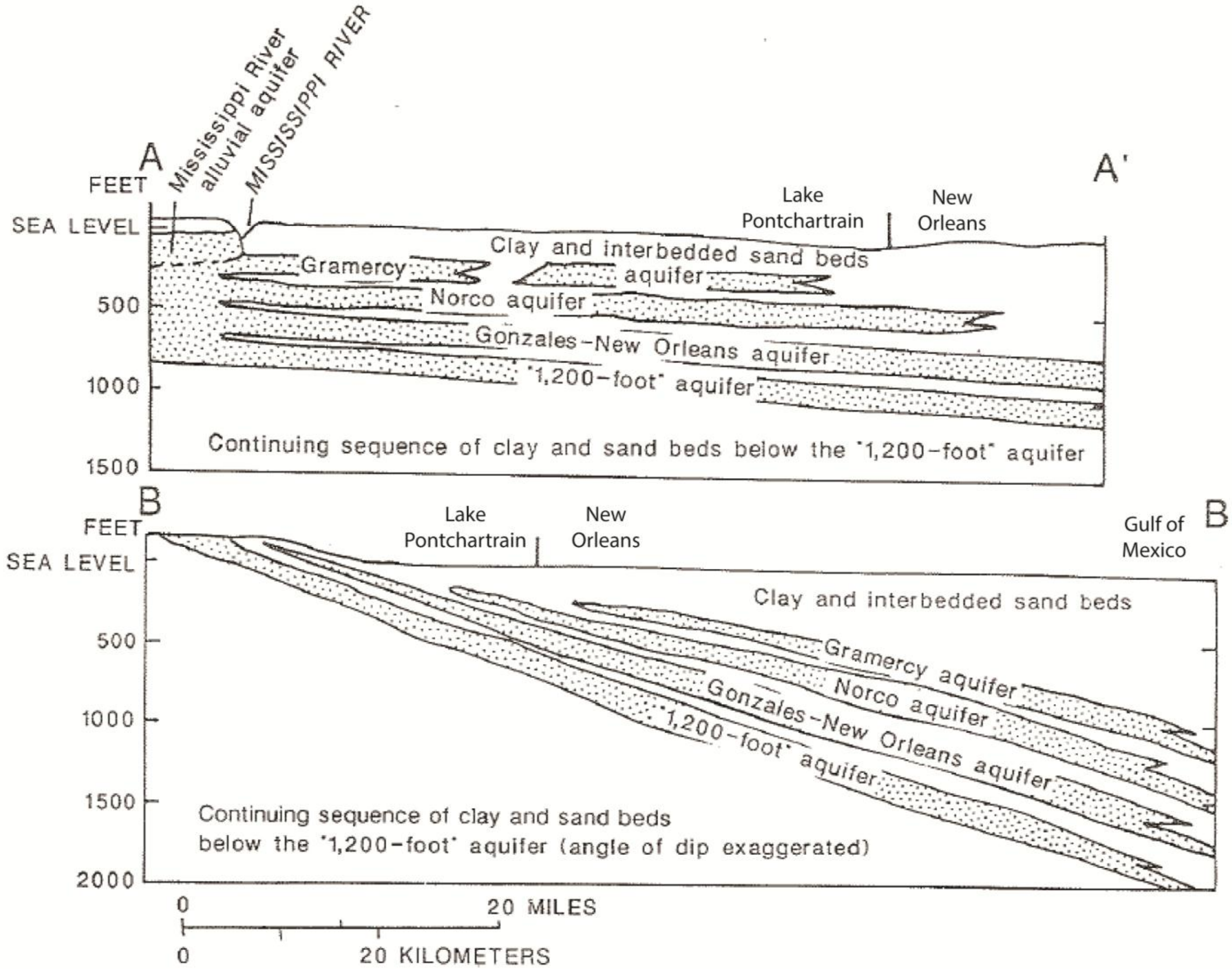

Figure 4. Generalized cross sections that characterize freshwater sands in the New Orleans area from east to west and north to south (Modified from Dial and Sumner, 1989). Cross section locations are highlighted in Figure 1.

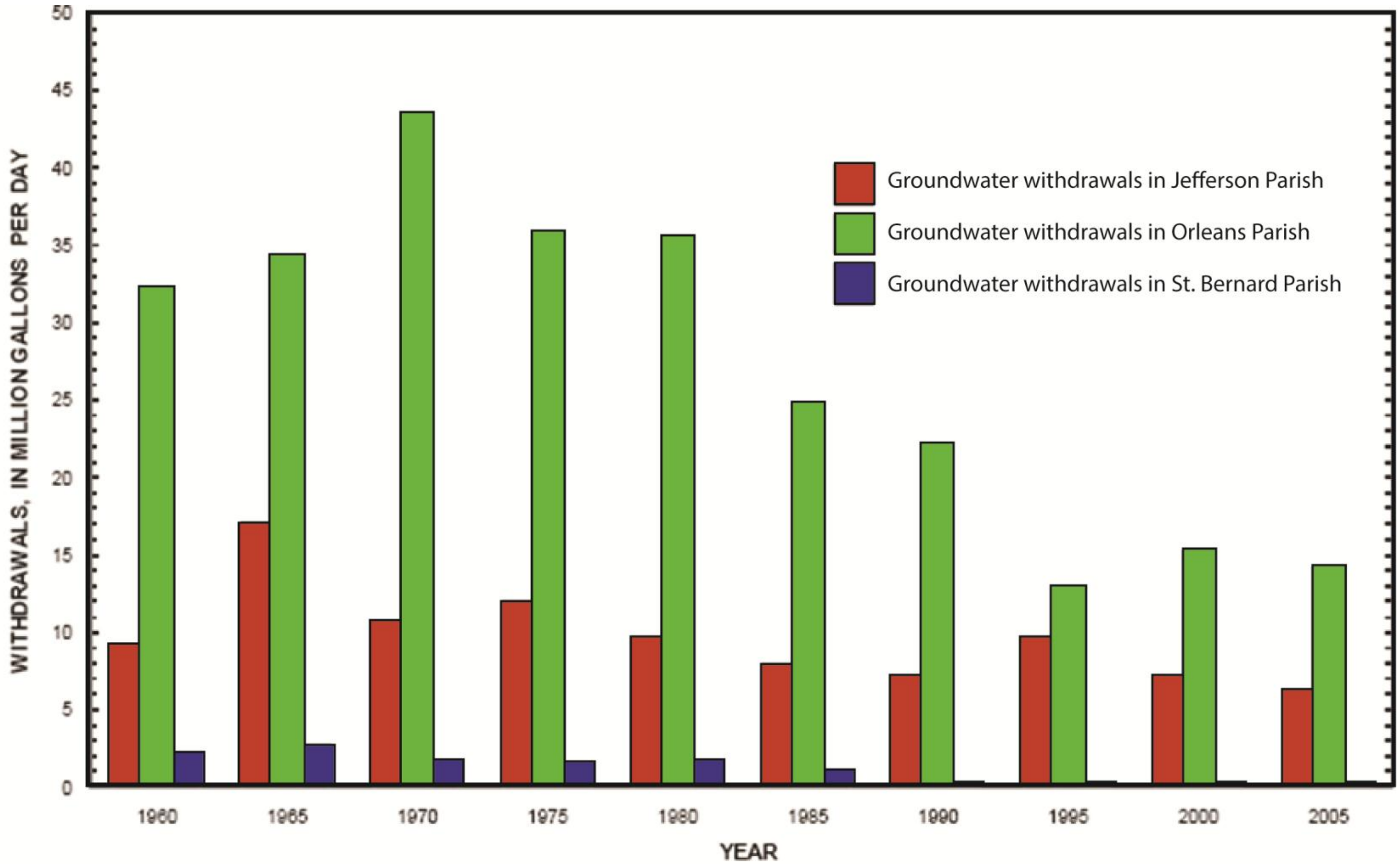

Figure 5. Average 5-year groundwater withdrawal rates from 1960 to 2005 (Modified from Prakken, 2009). Note the trend of decreasing pumping occurring after 1970 (the highest withdrawal of 60 MGal/d).

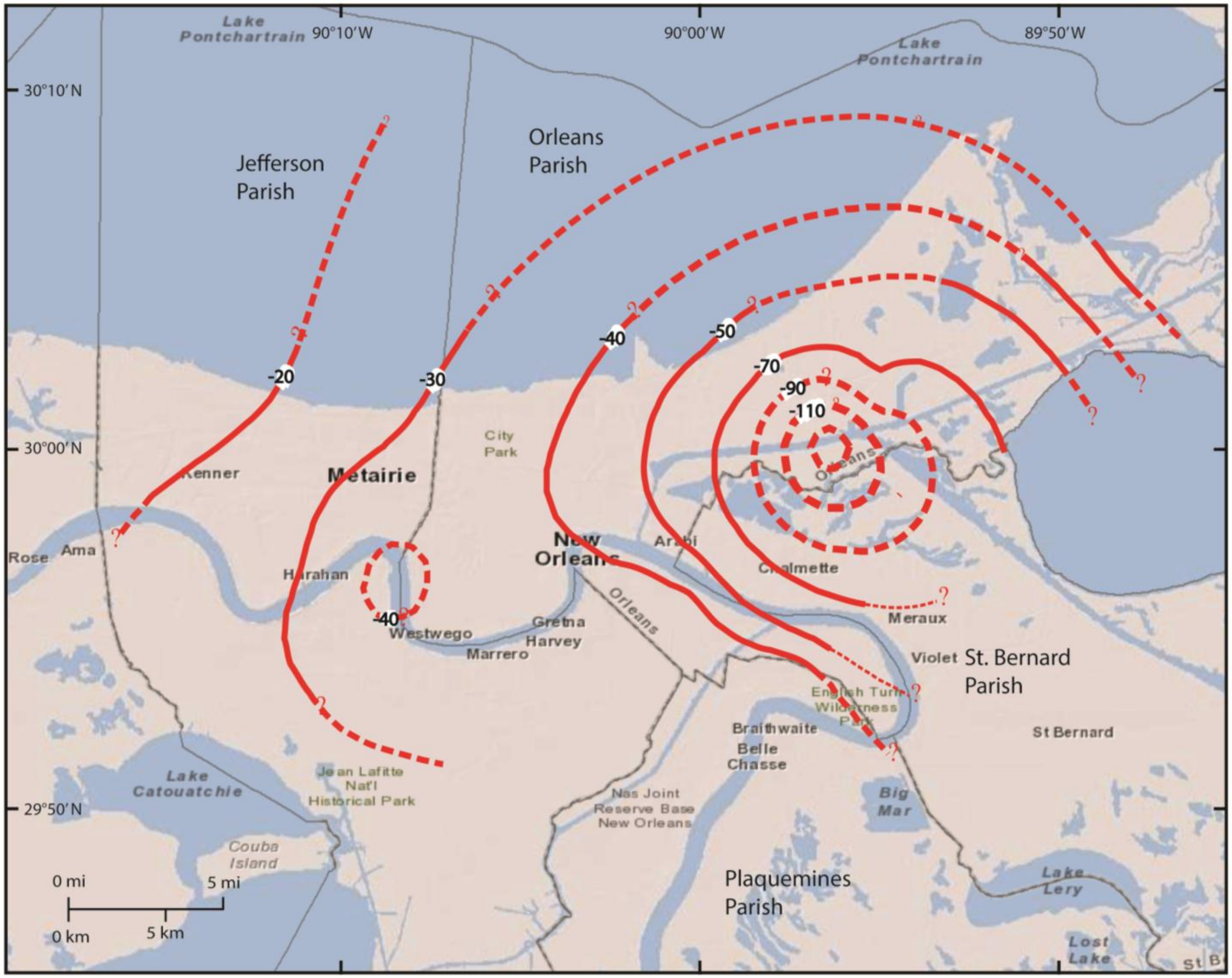

Figure 6. USGS Potentiometric Surface Map showing water level contours for the Gonzales-New Orleans Aquifer in 2009 within the study area (Modified from Prakken, 2009). Note the scale of the water level drawdown cone that has occurred as a result of groundwater withdrawal. Predevelopment groundwater flow was from north to south. Water level contours are in feet.

3. METHODS

3.1 Overwiew

Geophysical well logs were the primary source of data used to create the geologic cross sections. A total of 57 geophysical well logs were used for this study (Table 2). Figure 7 shows a typical log. A combination of spontaneous potential, resistivity and gamma ray logs were provided by the United States Geological Survey (USGS) and the Department of Natural Resources SONRIS. USGS, in addition, provided well screen intervals. USGS well logs contained information to a depth of on average a 1000 ft (300 m). SONRIS provided well logs that extended to greater depths, some as deep as 10,000 ft (3000 m).

The geophysical well logs in the study area were correlated along a series of approximately East-West and North-South trending cross sections (Fig. 8). Pumping well screen information was used at points between well logs where no data were available as a form of extra control on lateral continuity of the sand bodies (Fig. 9). This data set applied only to groundwater withdrawal wells within the Gonzales-New Orleans Aquifer unit, which has been more developed for groundwater use relative to other aquifers of the area.

A total of nine lithostratigraphic cross sections were drafted, with six north-south, three east-west. Each section included data for the depth interval of 0 to 2000 ft (600 m), though some logs did not extend this deep. Shallow depths of less than 1000 ft (300 m) correlate to USGS identified sands (Gramercy, Norco, Gonzales-New Orleans and the "1200 foot sand"), while depths between 1000 ft (300 m) and 2000 ft (600 m) correlated to units (Fig. 10) identified in McFarlan and LeRoy (1988). Gamma ray, SP and resistivity log depths were adjusted to account for Braden Head Flange height, Kelley Bushing height and ground level elevation so that depths are relative to the National Geodetic Vertical Datum of 1929.

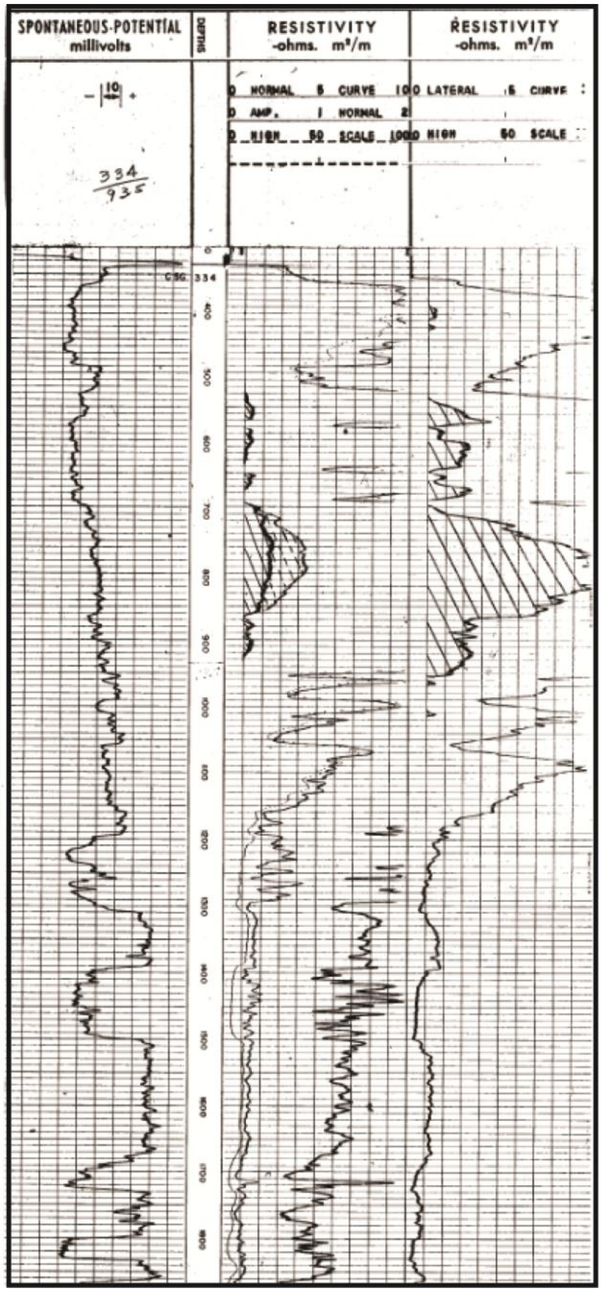

Figure 7. A well log interval for borehole B-9 in this study showing normal resistivities, lateral resistivity, and SP curves.

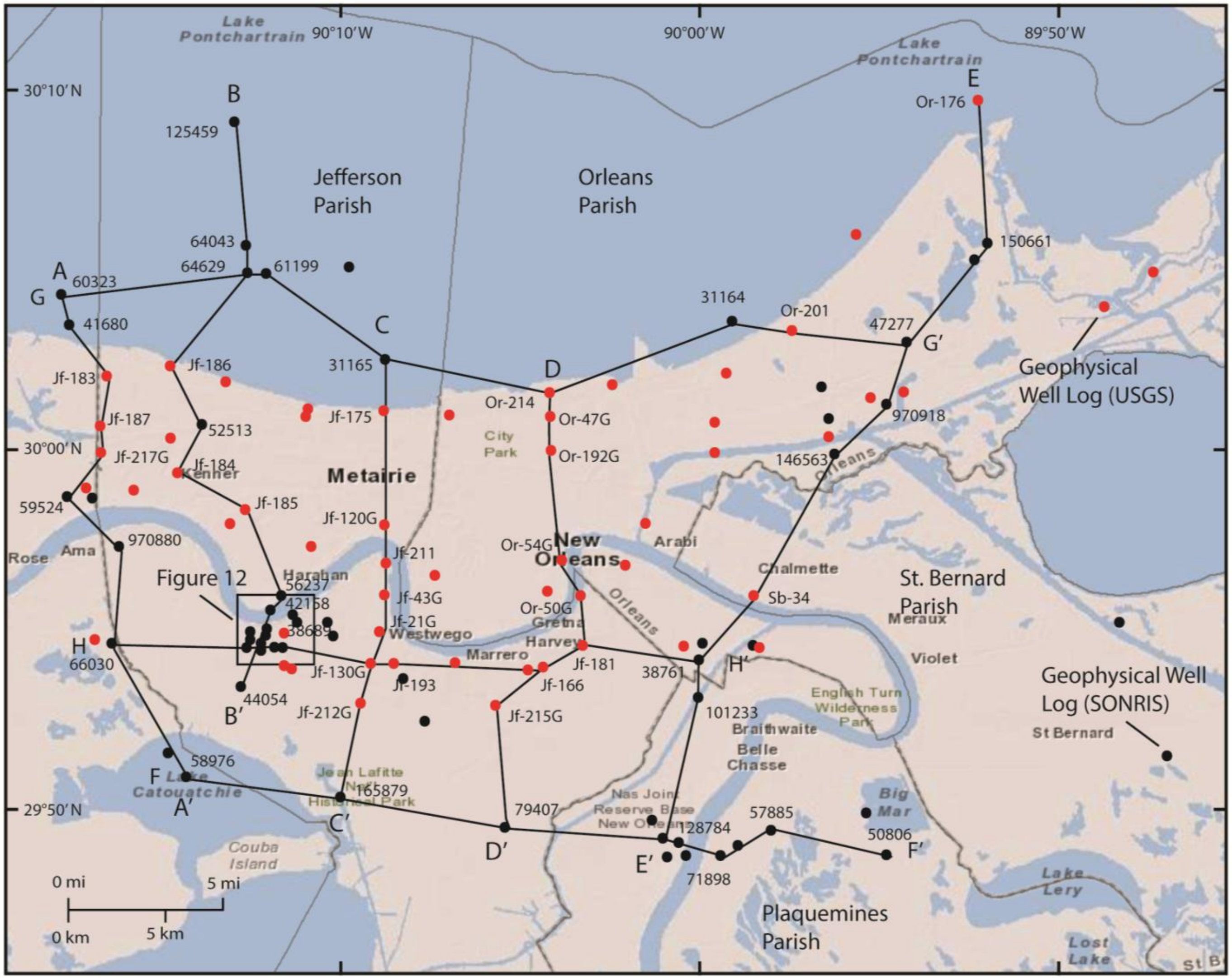

Figure 8. The study area is located in southeast Louisiana and uses geophysical well data from Jefferson, Orleans and St. Bernard Parish. The study area includes the Mississippi River, Lake Ponchartrain and various other water bodies (shown in blue). Black circles indicate the location of boreholes derived from SONRIS, while red circles mark the locations of borehole data provided by USGS.

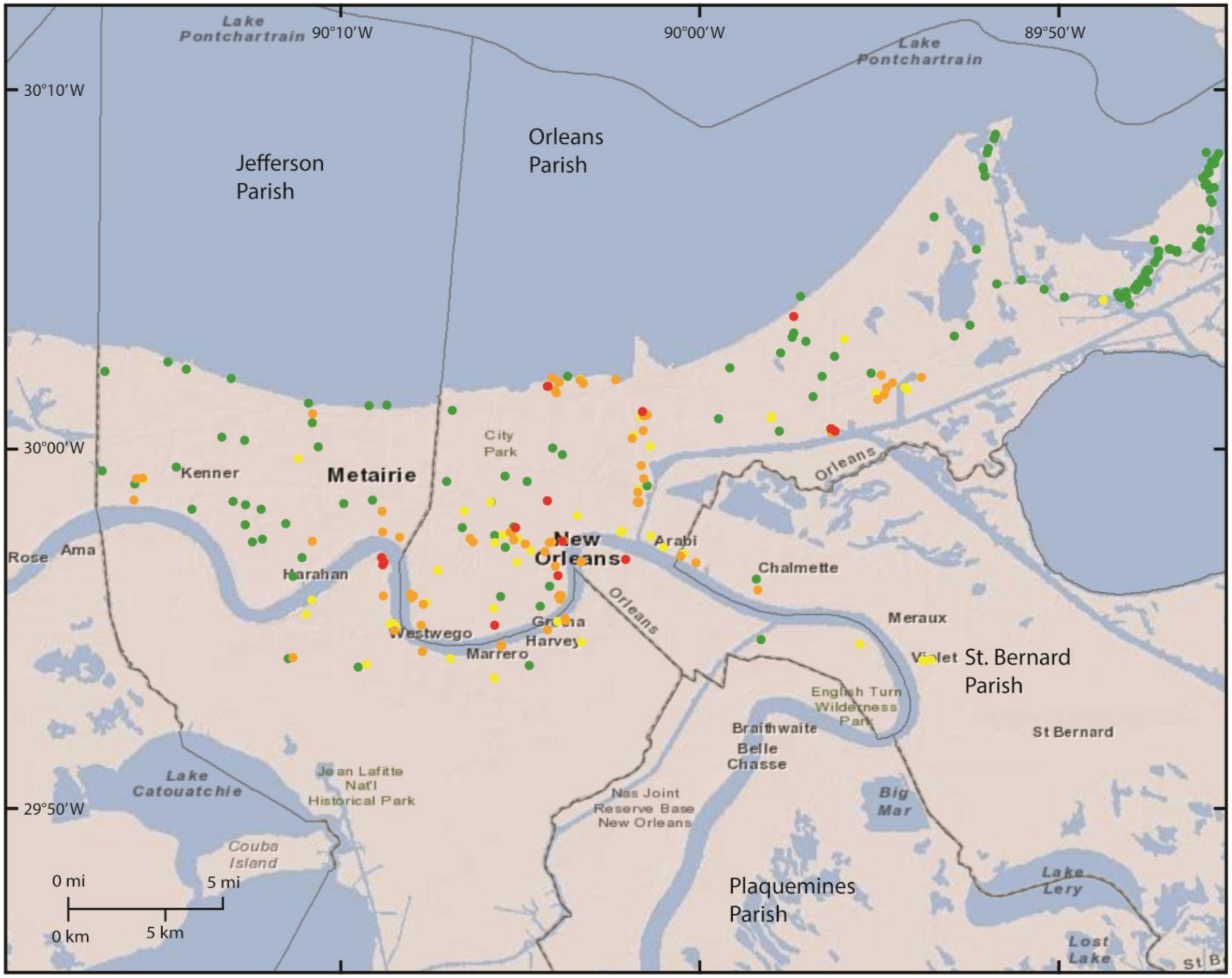

Figure 9. Color coded map of screen thicknesses in groundwater withdrawal wells of the Gonzales-New Orleans aquifer. Green wells indicate thicknesses of 10-40 ft. Yellow wells indicate thicknesses of 40-70 ft. Orange wells indicate thicknesses of 70-100 ft. Red wells indicate thicknesses of 100-130 ft. Wells are not assumed to represent full thickness of the aquifer.

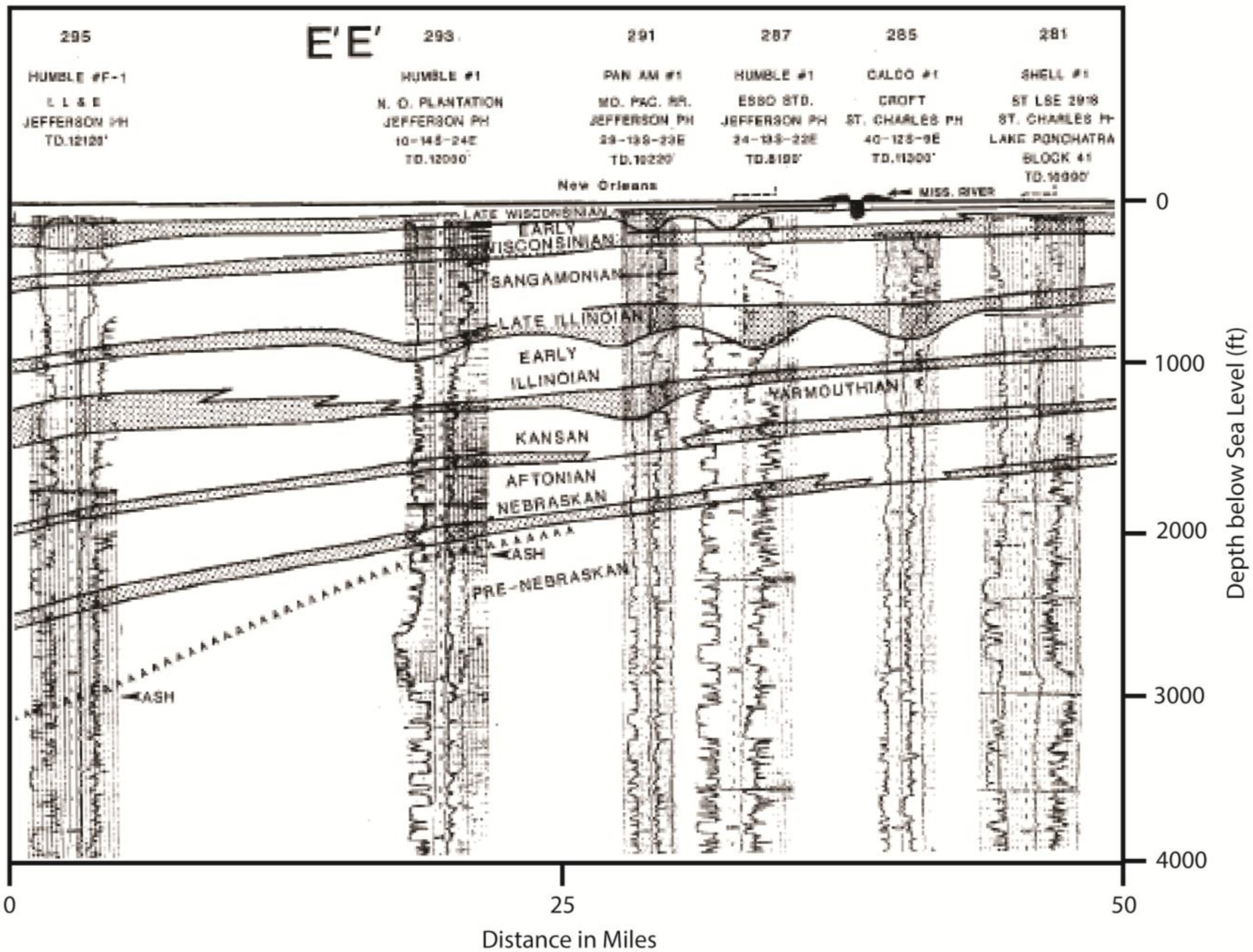

Figure 10. North to south cross section through parts of Jefferson Parish (Modified from McFarlan and LeRoy, 1988). Note the continuity of sedimentary zones along the cross section. Location of cross section highlighted in Figure 1.

3.2 Lithology Interpretation

Identification of sands versus clays was determined based on features unique to each type of geophysical well log. Spontaneous potential (SP) logs were generally used at depths greater than 1000 ft (300 m), as there was a more distinct contrast in SP response at these depths relative to shallow response. At these depths, sands were picked based on deviations from the shale baseline. Gamma ray logs did not extend below 1000 ft (300 m) in the study area. Sands were picked from this log based on low gamma ray values, because clays are known to give off more gamma rays than sands (Keys and MacCary, 1985). For depths of less than 1000 ft (300 m), where gamma ray logs were not available, resistivity values were used, specifically deviations in values between the short normal and the long normal log curves. These two log techniques explore fluid resistivity at different distances into the formation. When the borehole mud logging fluid infiltrates the formation, a deviation between the two curves is observable depending on the formation permeability. Infiltration effects are not detected by the long normal curve because the technique looks deeper into the formation, thereby preserving true formation resistivity. High permeability units (sands) show a change in the short normal curve due to infiltration and interaction with formation fluids, while low permeability units (clays) do not show a change. More detailed information into the properties and applications of the various geophysical methods can be found in Keys and MacCary (1985).

3.3 Subsurface Evaluation through Cross Sections

Sand units were correlated between well logs on cross sections by extending sand units halfway between logs, a technique utilized in other complicated subsurface regions in southern Louisiana (Wendeborn and Hanor, 2008; Chamberlain, 2012). Areas not correlated between logs were assumed to be clay/mudstone. The geophysical well logs did not contain a consistent set of markers, such as resistivity spikes, within the beds. The lack of these features made calculations of stratigraphic dip difficult. An estimated dip value of 0.1 degrees for sand beds was established by analysis of cross sections in the study area completed by McFarlan and LeRoy (1988) and Griffith (2003). Heterogeneity within the cross sections was quantified using the coefficient of variation equation:

$$Coefficient\ of\ Variation\ = \frac{Standard\ Deviation}{Mean}$$

where standard deviation refers to the standard deviation in thickness of sand beds within laterally connected sand bodies (sands that have overlap at midpoints between well logs), and mean refers to the average thickness of sand bodies within laterally connected sand bodies. Sand thickness at the individual geophysical well logs were used to determine both the standard deviation and mean thickness, as these are the only control points along the cross sections. For the purpose of this study, connected sand beds that have values of coefficient of variation higher than 0.1 are determined to have high heterogeneity, while connected sand beds with coefficients of variation less than 0.1 correspond with units having low heterogeneity.

3.4 Calculating Salinity from Resistivity Response

Well logs were additionally analyzed to calculate chloride concentrations within the Gonzales-New Orleans aquifer to constrain the location of saltier bodies of water. Resistivity was converted to chloride concentration through a series of equations. The first step involved the Archie equation: $F = a/\Phi^m$, where Φ is the porosity, F is the formation factor and (a, m) are the Humble constants. Based on values for unconsolidated sands, a = 0.62 and m = 2.15. Sand porosity was assumed to be 0.4 based on average values for medium-coarse sand. Water resistivity (R_w) was calculated from the equation $R_w = R_o/F$, where R_o is the resistivity reading from the long normal well log. Both R_w and R_o have units of ohm-meters. Groundwater conductivity (C_w) is the reciprocal of formation water resistivity (R_w), which was related to chloride concentration by the linear equation: Chloride concentration = $(0.3037 * C_w) - 151.09$. This equation was based on the relationship between sampled values of chloride concentration and specific conductance from aquifer field tests in the study area (Fig. 11). In many well logs, fresher water was underlain by saltier water within aquifer units. In these well logs, the saltier water resistivity was used for analysis.

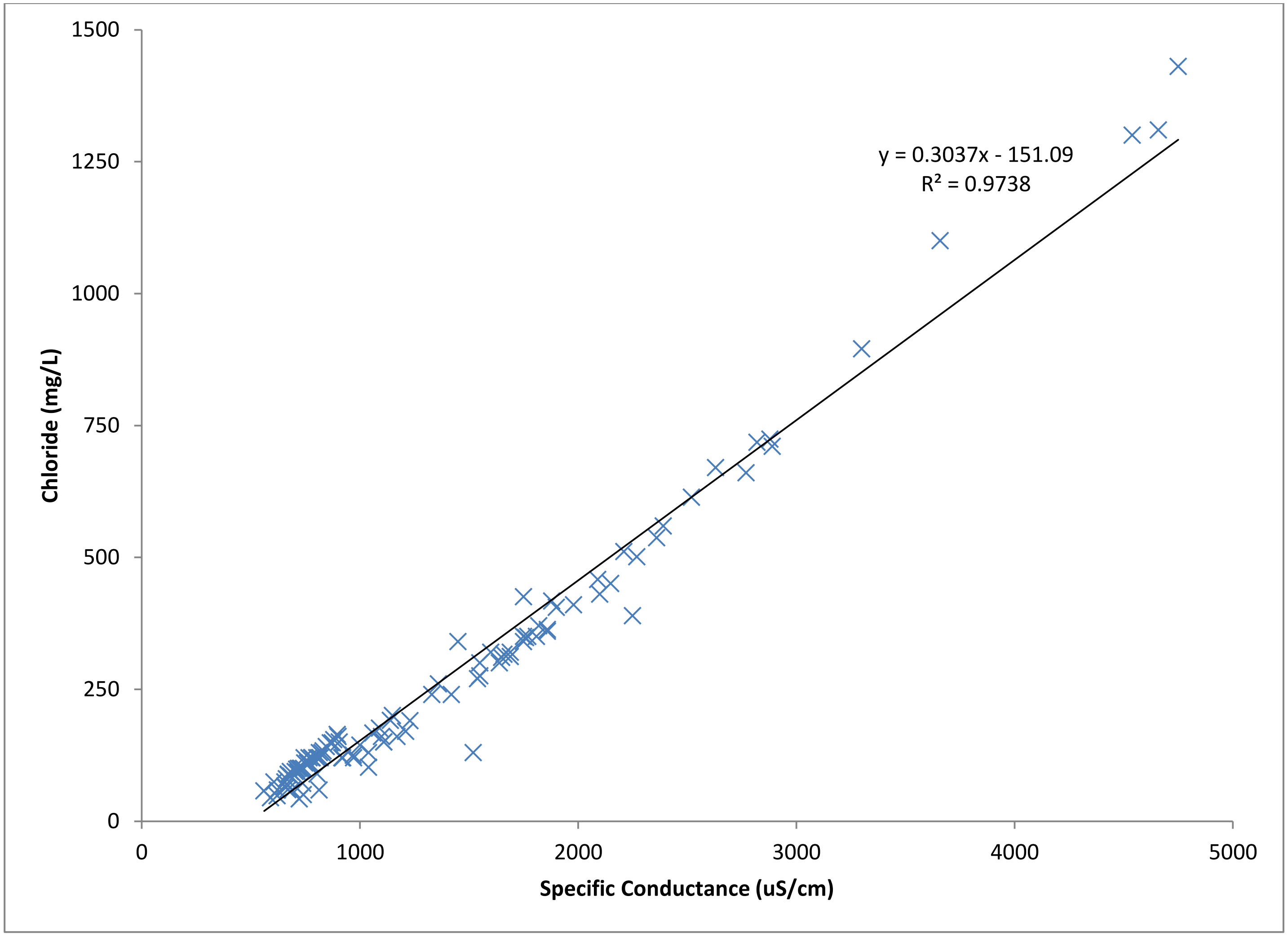

Figure 11. Linear relationship between specific conductance and chloride concentration for USGS observation wells within the study area. The linear relationship was used to relate resistivity well log analysis to formation chloride concentrations.

4. RESULTS/DISCUSSION

4.1 Lithologic Continuity

One of the main goals of this study was to provide an accurate representation of the subsurface architecture and discuss the implications of this architecture to current groundwater problems of the New Orleans area. Results of the subsurface architecture are presented in nine cross sections. Two of these cross sections, shown in Figure 12 and 13, present a picture of the stratigraphy at two different spatial scales. Figure 12 is approximately 15,000 ft (5000 m) across, whereas Figure 13 is approximately 135,000 ft (45,000 m) across.

The scale of Figure 13 is large, with a separation of logs generally of over 10,000 ft (3000 m), and shows a high amount of heterogeneity in the subsurface. There is a high amount of lateral connectivity between sand units, but there are numerous locations where sand units thin and pinch out. At this scale, the most laterally continuous sand is the unit corresponding to the GZNO aquifer unit, which has a coefficient of variation in sand thickness of 0.35. Shallower units (correlating to the USGS Norco and Gramercy units) do not appear to have connectivity between logs and are often thin or missing. There is a thin sand bed above the GZNO unit that appears visible in Figure 13, though only in a few logs. At this scale, the sand unit appears to share some connection with the GZNO sand, and is usually separated by a clay layer approximately 25 to 75 ft (8 to 25 m) thick. While this sand unit appears in other cross sections, it does not appear continuously throughout the section. Rollo (1966) recognized this unit, but only in northwestern Orleans parish, where he characterized it as a thin upper layer of the Gonzales-New Orleans aquifer. This study shows the sand in areas outside of Orleans parish, where it does not always appear as the thinner of the two units comprising the GZNO (Figures 14, 15, 16, 17, 18, 19, 20). Deeper in section E-E’ and towards the south (well E-9), there appear

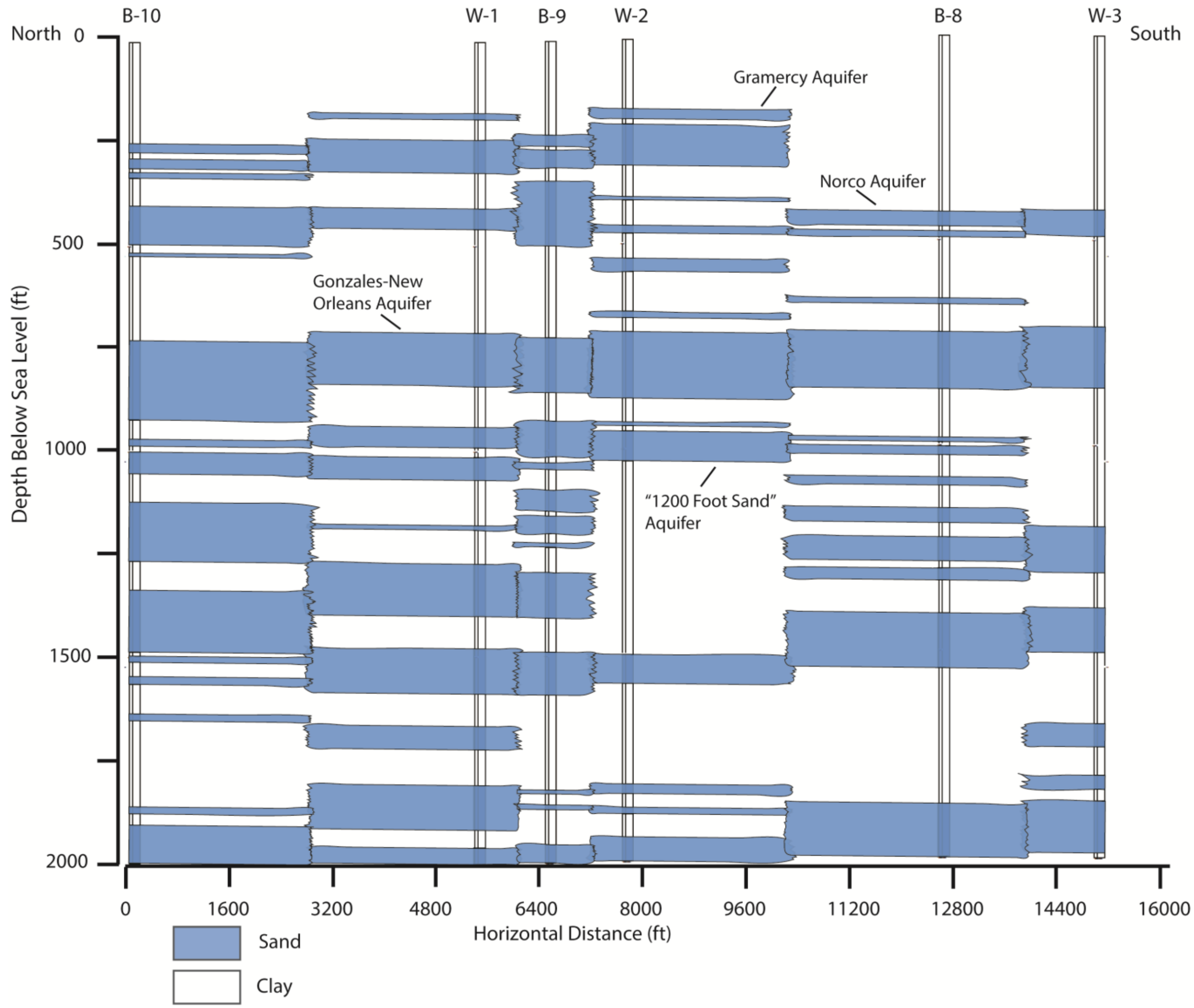

Figure 12. Lithologic cross section (I-I') showing spatial distribution of sands and mudstones (based on SP, Resistivity and Gamma Ray log response) as well as lateral correlation. Sands are indicated in blue, mudstones are indicated by white. Section includes a depth interval of 0 ft (0 m) to 2000 ft (600 m). Wells are correlated by extension of sand thickness laterally halfway between logs.

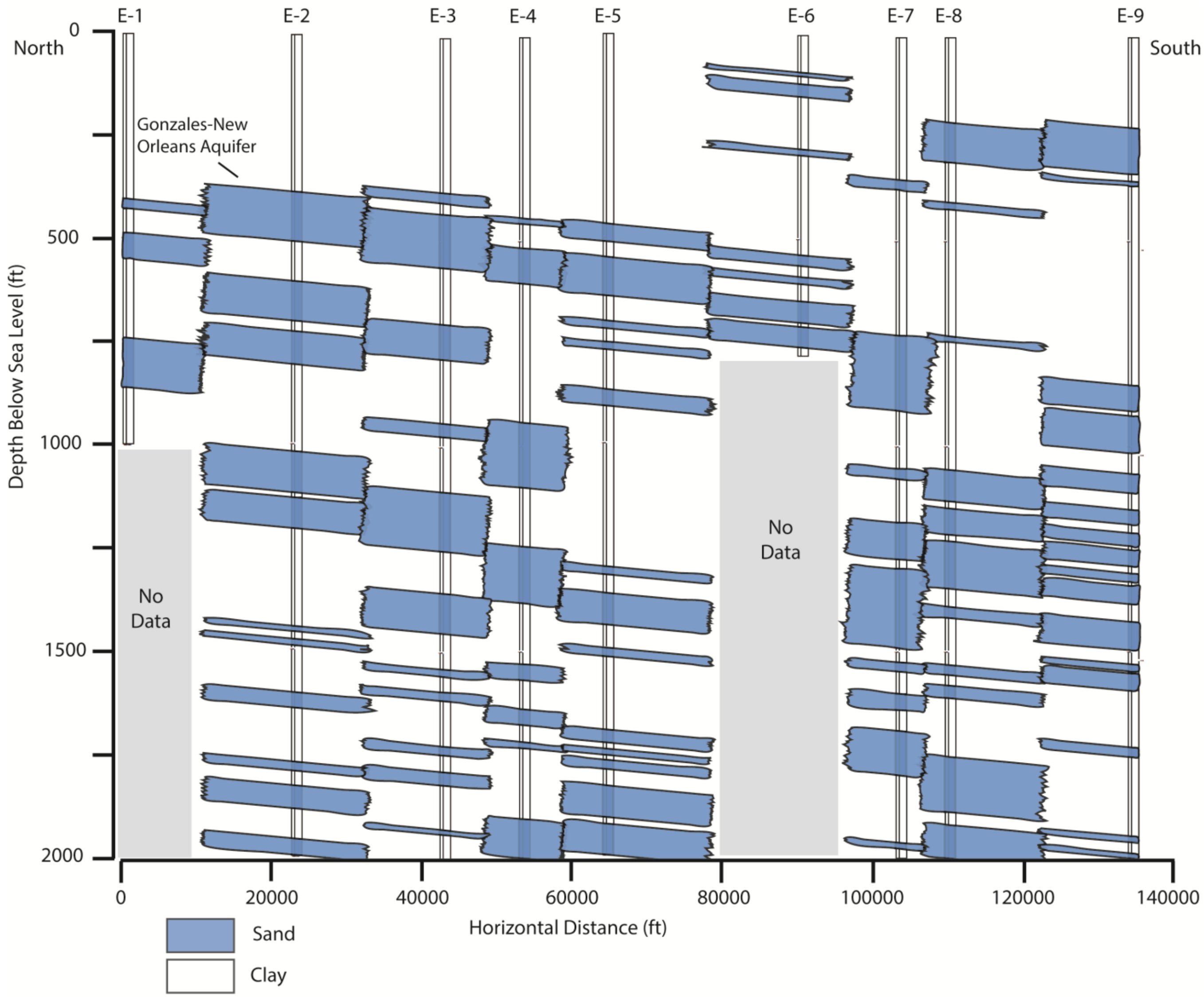

Figure 13. Lithologic cross section (E-E') showing spatial distribution of sands and mudstones (based on SP, Resistivity and Gamma Ray log response) as well as lateral correlation. Sands are indicated in blue, mudstones are indicated by white. Section includes a depth interval of 0 ft (0 m) to 2000 ft (600 m). Wells are correlated by extension of sand thickness laterally halfway between logs.

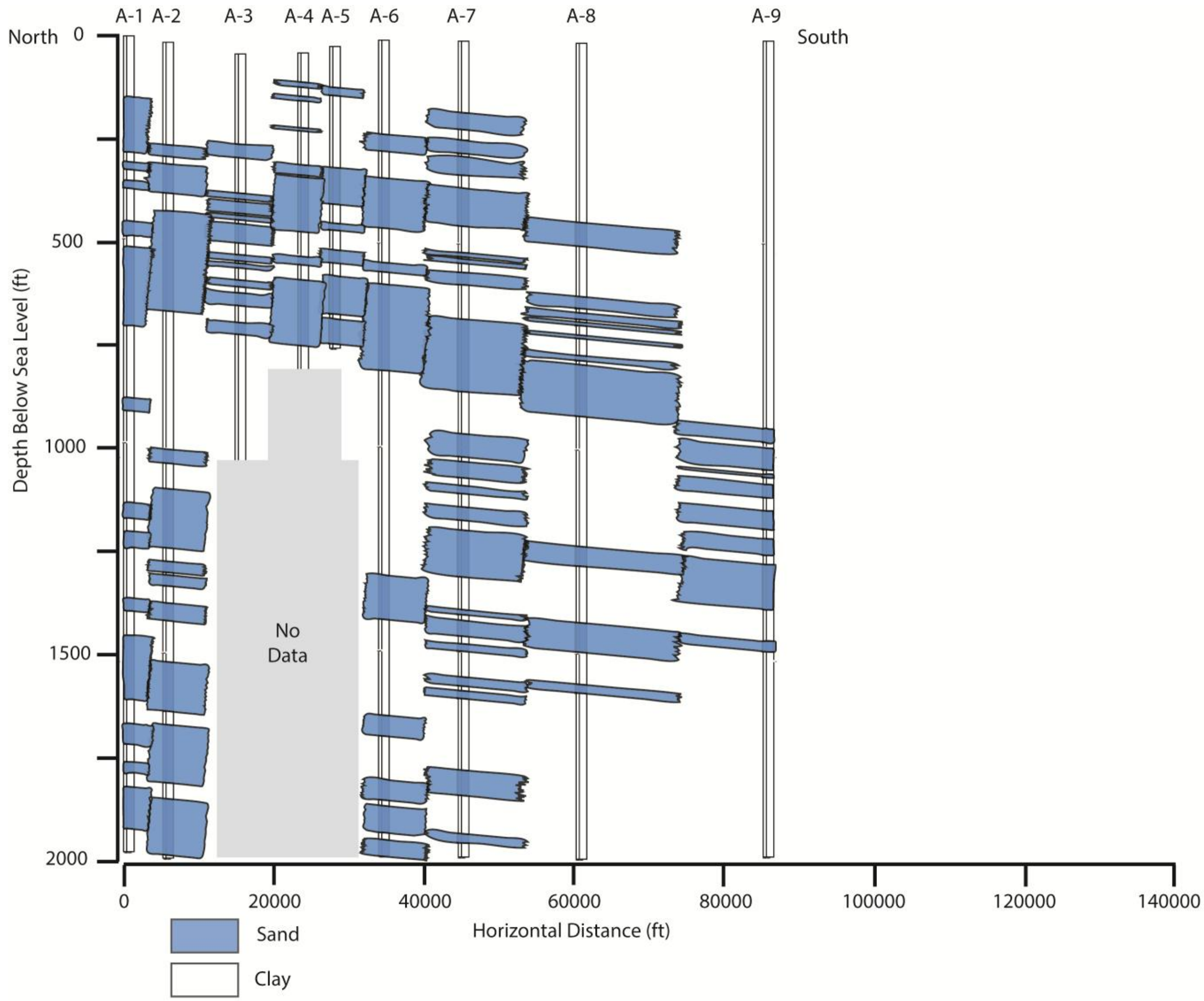

Figure 14. Lithologic cross section (A-A') showing spatial distribution of sands and mudstones (based on SP, Resistivity and Gamma Ray log response) as well as lateral correlation. Sands are indicated in blue, mudstones are indicated by white. Section includes a depth interval of 0 ft (0 m) to 2000 ft (600 m). Wells are correlated by extension of sand thickness laterally halfway between logs.

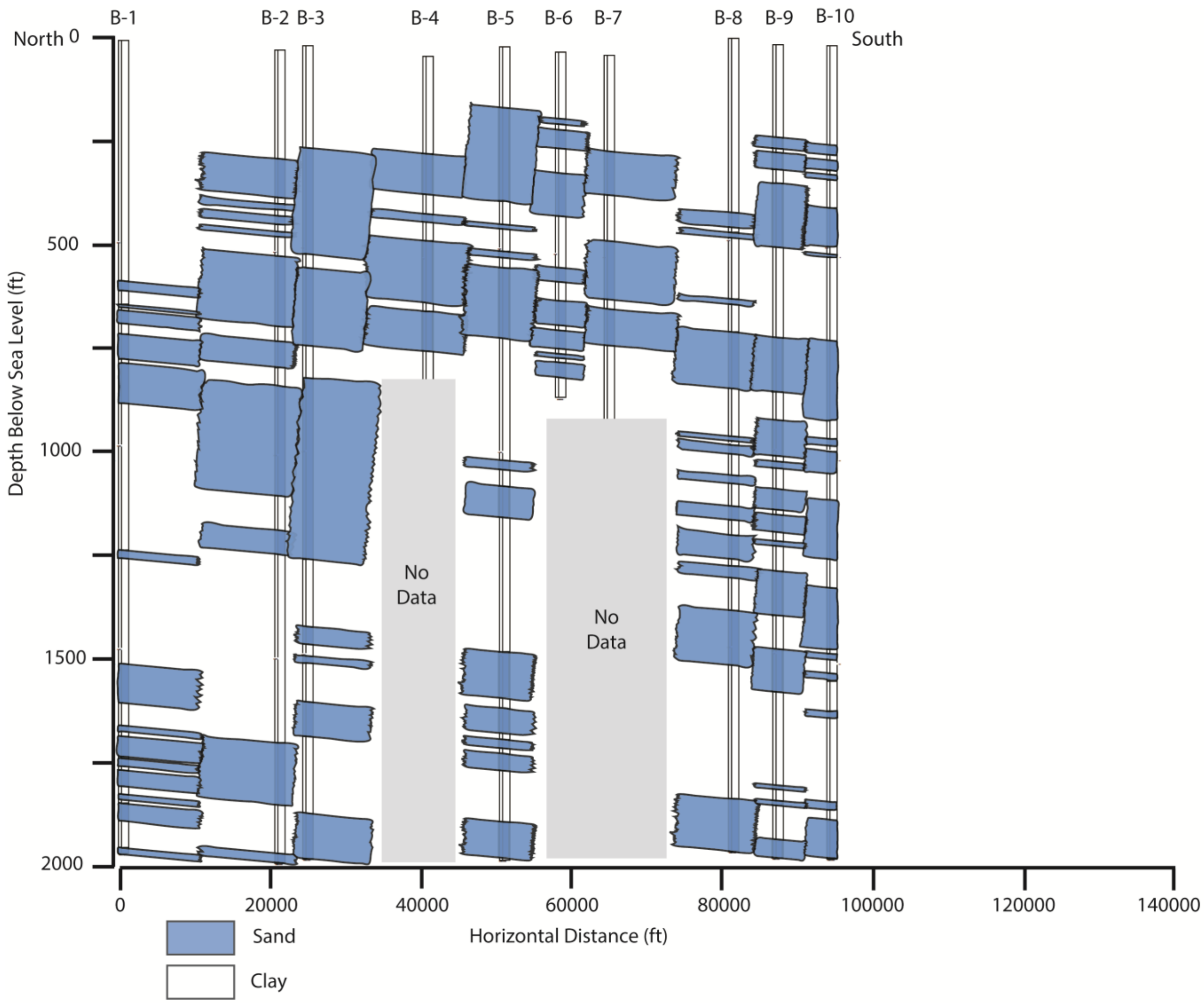

Figure 15. Lithologic cross section (B-B') showing spatial distribution of sands and mudstones (based on SP, Resistivity and Gamma Ray log response) as well as lateral correlation. Sands are indicated in blue, mudstones are indicated by white. Section includes a depth interval of 0 ft (0 m) to 2000 ft (600 m). Wells are correlated by extension of sand thickness laterally halfway between logs.

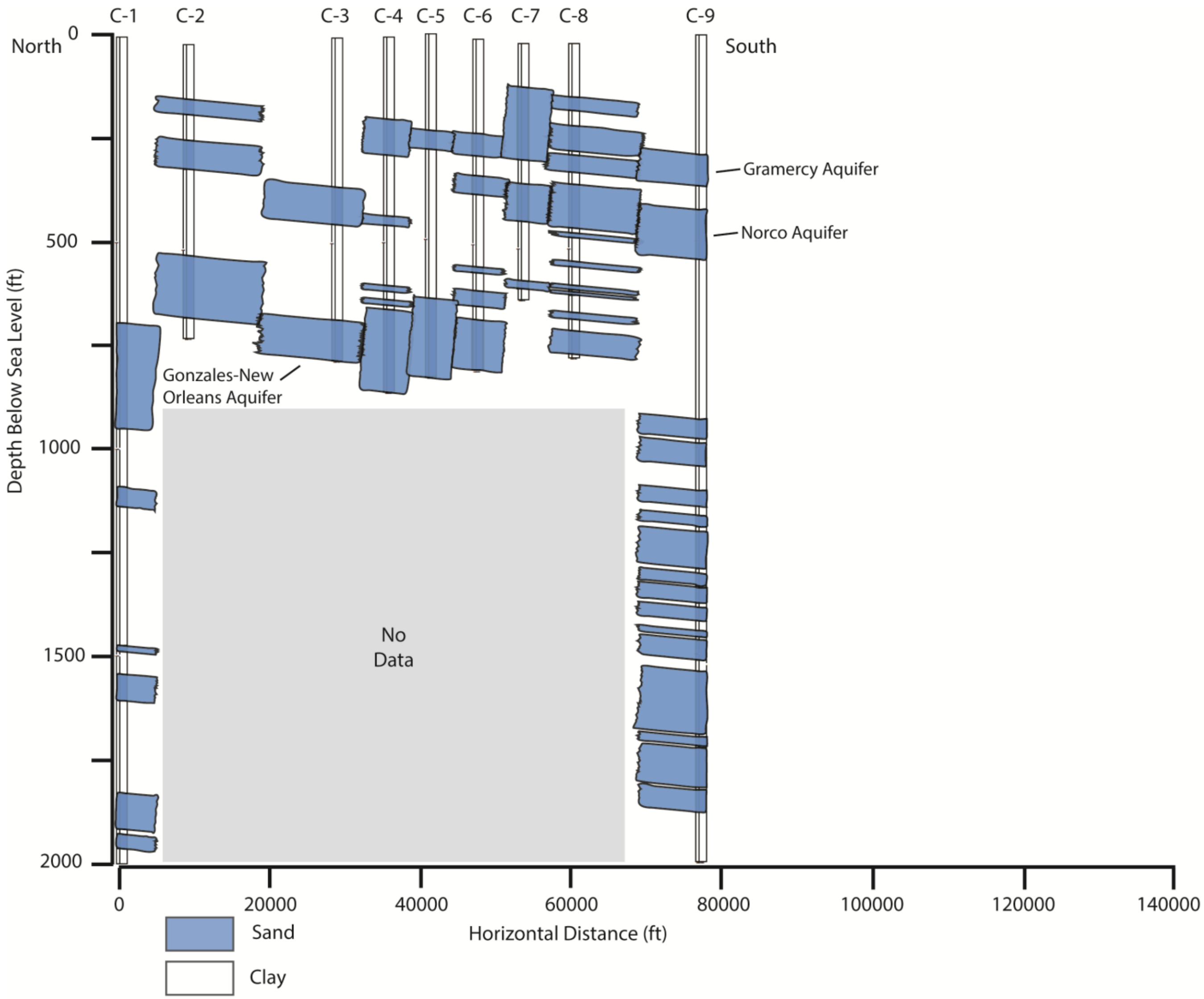

Figure 16. Lithologic cross section (C-C') showing spatial distribution of sands and mudstones (based on SP, Resistivity and Gamma Ray log response) as well as lateral correlation. Sands are indicated in blue, mudstones are indicated by white. Section includes a depth interval of 0 ft (0 m) to 2000 ft (600 m). Wells are correlated by extension of sand thickness laterally halfway between logs.

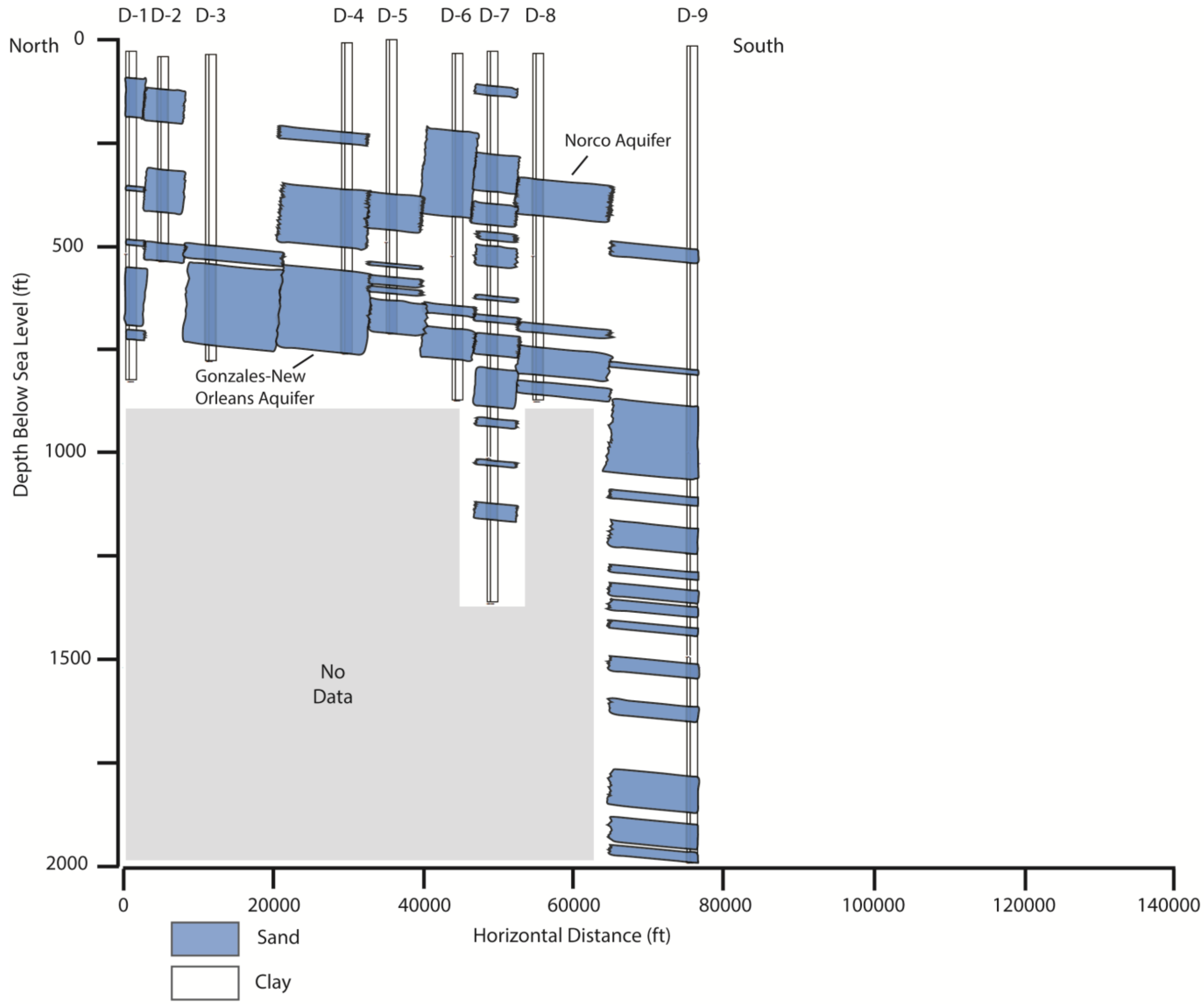

Figure 17. Lithologic cross section (D-D') showing spatial distribution of sands and mudstones (based on SP, Resistivity and Gamma Ray log response) as well as lateral correlation. Sands are indicated in blue, mudstones are indicated by white. Section includes a depth interval of 0 ft (0 m) to 2000 ft (600 m). Wells are correlated by extension of sand thickness laterally halfway between logs.

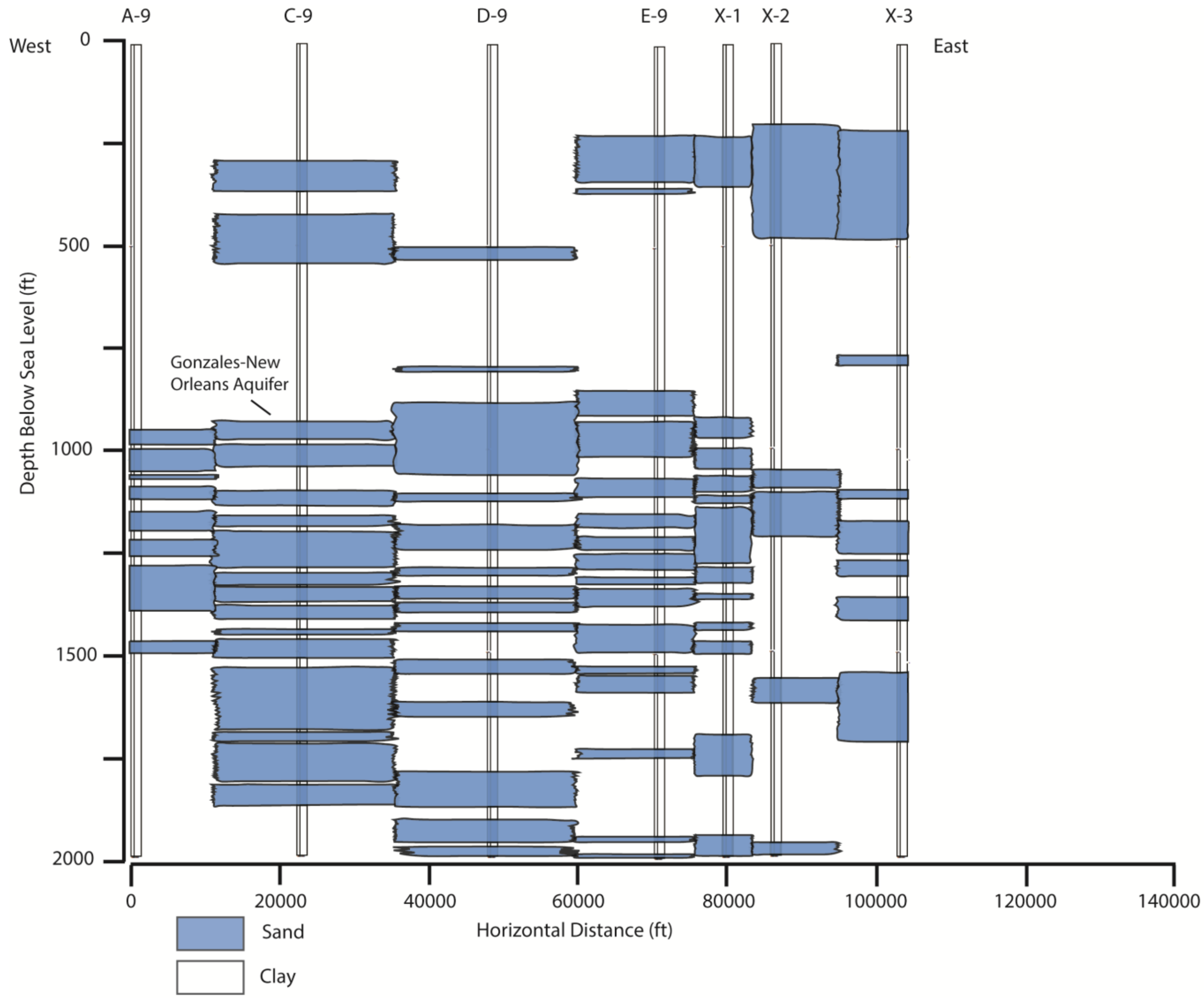

Figure 18. Lithologic cross section (F-F’) showing spatial distribution of sands and mudstones (based on SP, Resistivity and Gamma Ray log response) as well as lateral correlation. Sands are indicated in blue, mudstones are indicated by white. Section includes a depth interval of 0 ft (0 m) to 2000 ft (600 m). Wells are correlated by extension of sand thickness laterally halfway between logs.

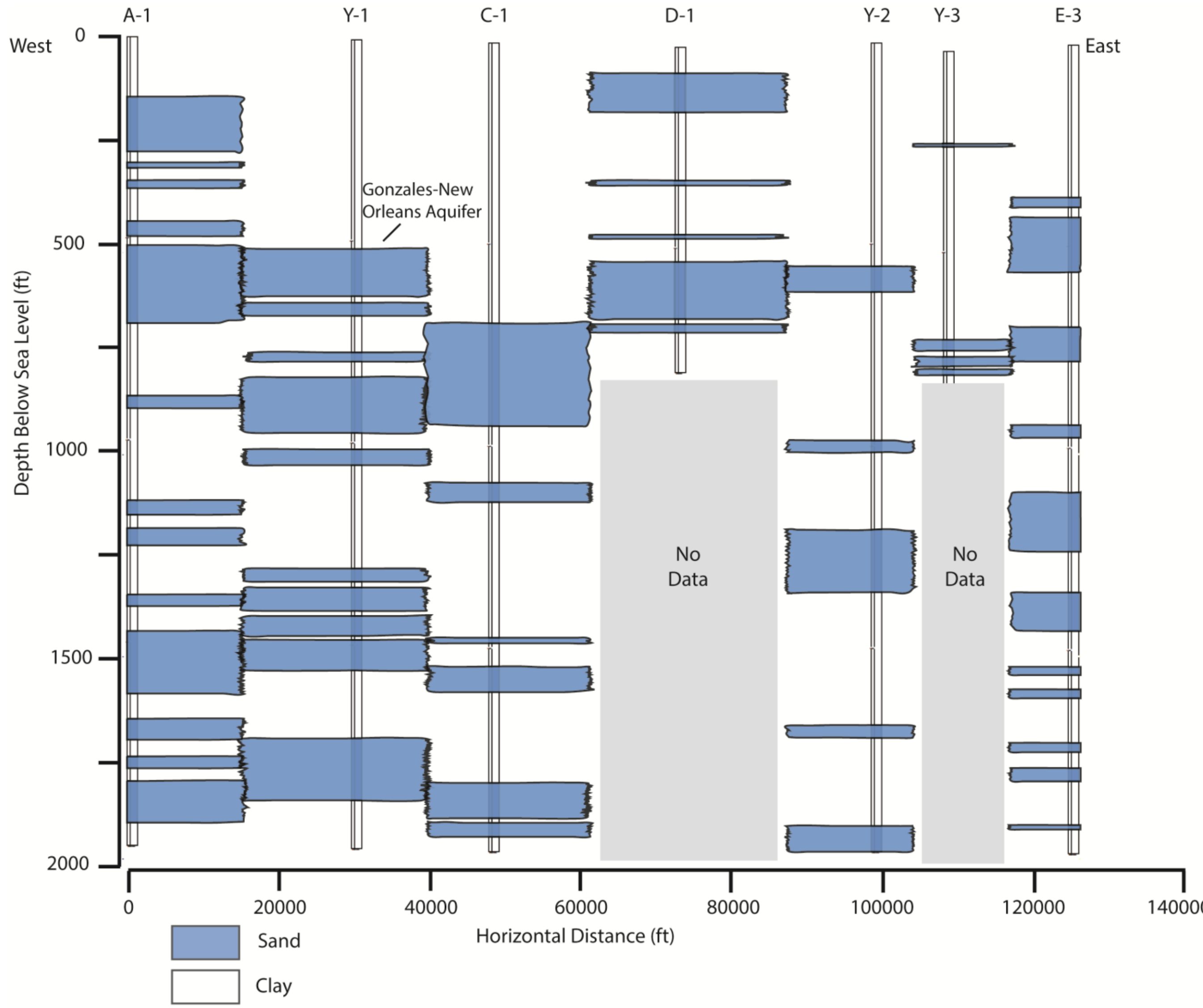

Figure 19. Lithologic cross section (G-G') showing spatial distribution of sands and mudstones (based on SP, Resistivity and Gamma Ray log response) as well as lateral correlation. Sands are indicated in blue, mudstones are indicated by white. Section includes a depth interval of 0 ft (0 m) to 2000 ft (600 m). Wells are correlated by extension of sand thickness laterally halfway between logs.

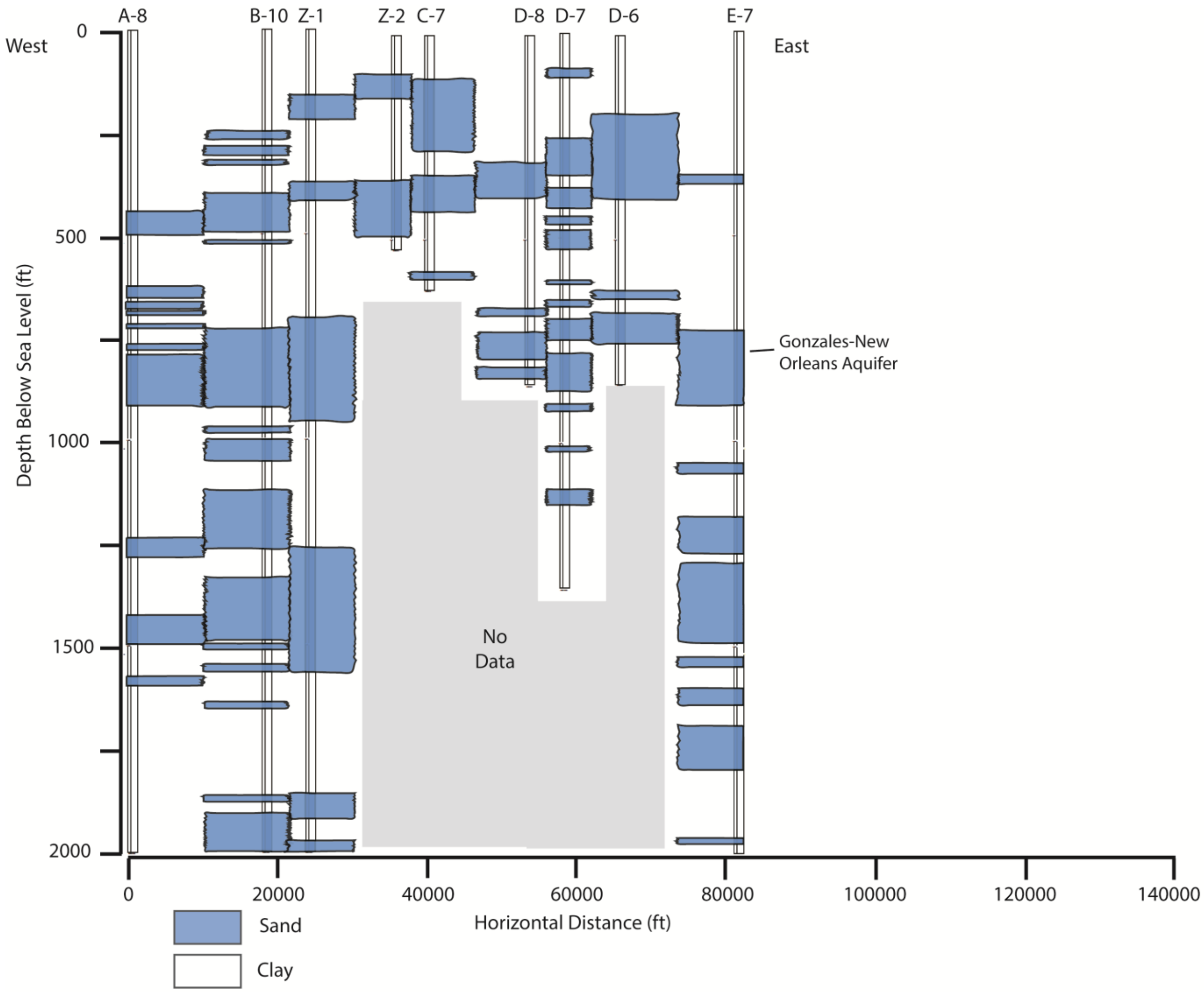

Figure 20. Lithologic cross section (H-H') showing spatial distribution of sands and mudstones (based on SP, Resistivity and Gamma Ray log response) as well as lateral correlation. Sands are indicated in blue, mudstones are indicated by white. Section includes a depth interval of 0 ft (0 m) to 2000 ft (600 m). Wells are correlated by extension of sand thickness laterally halfway between logs.

to be bodies of sand that are separated by very thin clay layers, as opposed to thicker clay layers seen to the north.

Previous studies (Dial and Sumner, 1989; Tomaszewski, 2003; Prakken 2009) show both the Gramercy and the Norco aquifer as thin or missing in the eastern region of the New Orleans area. Figures 13, 16, and 17 are north to south cross sections through the eastern region of the area. Figure 13, the easternmost cross section, does show the Gramercy and the Norco aquifers as thin/missing. However, in Figure 17, there is a connected sand unit overlying the GZNO aquifer that corresponds to the Norco aquifer. Figure 16 is slightly to the west of Figure 17 and shows both the Gramercy and the Norco aquifers as connected units of sand approximately 100 ft (30 m) thick in some well logs.

Figures 18, 19, and 20 show east to west cross sections in the study area. Sands are generally connected between adjacent logs within the Gonzales-New Orleans aquifer, but other units are more difficult to distinguish, in some cases due to lack of data. These cross sections clearly show that the GZNO is shifting to larger depths with each step to the south. In the north (Fig. 19), the top of the GZNO is approximately 500 ft (150 m) deep. Figure 20 shows the top at 750 ft (250 m) deep, and Figure 18 (the southernmost cross section) shows the top at 1000 ft (300 m). Deeper units are difficult to correlate to units identified by McFarlan and LeRoy (1988) in Figure 18, as many units are now thinner and heavily interbedded with thin clay layers.

One of the objectives of this study was to analyze the lateral extent of the sand bodies that compose the New Orleans Area Aquifer System. Due to the spacing of many of the geophysical logs, sands appear to abruptly pinch out and become interbedded with clays between control points. It is clear that geologically important processes occurred between data points, but the scale is too large to resolve this information. This created a need to analyze sections of the study area where many wells were clustered over a small distance. Figure 12 is a section through one of the clusters.

In Figure 12, it is possible to relate sand layers to the current USGS equivalent for the region. The four main aquifers of the USGS naming convention (Norco, Gramercy, Gonzales-New Orleans, and the “1,200 foot sand”) are visible at this scale and appear to have a good degree of horizontal connectivity between geophysical well logs. The sandy units correlating to the Gonzales-New Orleans (GZNO) aquifer appear to have the most consistency between well logs at this scale (Fig. 12). The coefficient of variation in connected sand thickness for the GZNO at this scale is 0.094. There are very few interbedded clays within the aquifer at many well logs, and 88 percent of the total sand thickness is connected between well logs.

However, the issue of lateral continuity is present even at this scale, as many sand bodies drastically change in thickness, appear missing, or increase in clay content. For example, the coefficient of variation in connected sand thickness in the Norco aquifer is 0.504, a value corresponding to high heterogeneity. An example of the heterogeneity within the Norco is observed where the aquifer transitions from one sand in well B-9 that is 158 ft (50 m) thick into two sands at well W-2 that are a combined 30 ft (10 m) thick in under 1000 ft (300 m). Other examples are displayed in the ‘1,200 foot sand’ and deeper units. The ‘1,200 foot sand’ appears as a combination of two sands separated by a thin clay layer that has a mean thickness of 15 ft (5 m). However, the clay layer changes in vertical position between logs, with a maximum change of 72 ft (24 m) between wells B-9 and W-2. Other sand units below the “1,200 foot sand” are not described by the USGS. These units are described by McFarlan and LeRoy (1988) to display full lateral connectivity. However, the results of Figures 12-20 do not show such a high lateral continuity. In fact, deeper sand units in the study area display more lateral connectivity between sand units at highly different vertical depths with units separated by significantly thick clay units up to 100 ft (30 m). An example of this is seen between logs B-9 and W-1 in Figure 12, where one sand unit in B-9 (depth of 1300 ft) appears connected with two sand units that are separated by 80 ft (25 m) of clay in W-1. An example of units pinching out is also seen in Figure 12 at well log B-9 and W-2. Sands within log B-9 have no equivalent in log W-2 between 1000 ft (300 m) and 1500 ft (500 m). It is apparent that if these differences can exist at spacing of 1,000 ft (300 m), then the larger scale cross sections (e.g. Fig. 13) do not capture the complexity and heterogeneity of the system, and overestimate sand content in certain areas, while underestimating in others. The overall heterogeneity observed in cross sections at both small and large scale demonstrated a need to verify if the discontinuous nature of sand bodies was plausible based on the depositional patterns of these units.

4.2 Depositional Interpretation

Numerous avenues of depositional environment interpretation are possible when considering the New Orleans Pleistocene deposits. The Pleistocene was characterized by many changes in sea level, the result of changes in the volumes of continental ice sheets. This change in sea level (an allogenic process) is one source of control acting on the style of deposition. The other controlling force is channel avulsion (an autogenic process), the abandonment of one channel in favor of a more hydraulically efficient channel. Miall (2010) estimates allogenic forces to operate on the scale of 10^4 to 10^7 years, whereas autogenic forces occur on timescales of 10^3 to 10^4 years. Based on these timescales, many autogenic changes can occur during a single allogenic event. One more process that operates on a smaller scale is channel and bar migration (Coleman, 1964). These forces produce two main hypotheses for deposition, a fluvial deposition hypothesis and a deltaic deposition hypothesis. Autogenic processes can lead to both fluvial and deltaic deposition, but the specific deposition type depends on sea level position. Figure 21 shows the location of lowstand deltas extended far (100 miles) into the Gulf relative to the study area during the Pleistocene. Meaning that during periods of lower sea level, deltaic deposition is not possible in the study area, and sedimentation instead occurs via fluvial deposition. However, Figure 3 shows that during sea level highstands, deltaic deposition centers are shifted into the study area, meaning that there is a contribution from deltas to the subsurface stratigraphy as well. These sediments were deposited over the last the few million years, during which there were many changes in sea level. Both types of depositional environments were present in the study area based on allogenic and autogenic forcing. The combination of both the fluvial and deltaic hypotheses is capable of explaining the depositional history of the New Orleans sediments.

One of the questions this study addressed was the determination of the depositional history of the sediments that comprise the New Orleans subsurface. The question revolves around the location of the study area relative to the continual changes in environment caused by the allogenic and autogenic forces. The first part of this section will focus on the deltaic hypothesis. Channel avulsion forces new deltas to be formed elsewhere when hydraulically preferred paths become available, which modern analogs show as a cyclic process that has occurred continuously in southern Louisiana during the last 7500 years (Kolb and Van Lopik, 1966; Frazier, 1967; Boyd, 1988). Based on modern analogs, it is likely that this process has occurred during Pleistocene sea level highstands as well.

Today, the Mississippi River flows through the study area before branching into the many distributaries of the modern Bird's Foot delta located southeast of the study area. This elongate style delta differs from previous iterations of the Mississippi River delta, including the lobate

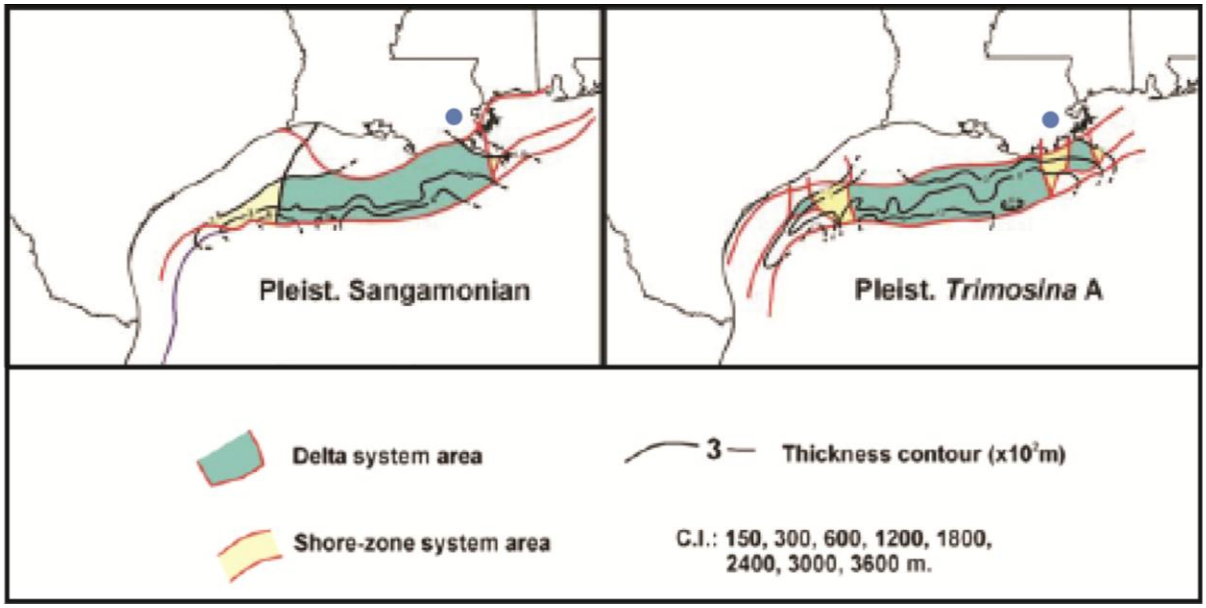

Figure 21. Lowstand deltaic depositional systems in Pleistocene sediments in the northern sedimentary basin of the Gulf of Mexico (Modified from Galloway 2001). Study area location is indicated by a blue circle.

style Lafourche delta system. The scale of the delta systems is important in relation to the scale of the study area. Elongate deltas, such as the Modern Mississippi, are not more than 10 miles across (Fisher, 1969), not large enough to cover the study area, whereas the lobate Lafourche delta is approximately 50 miles across in some locations (Fig. 22), much larger than the study area. It is also important to point out that the sand units extend outside of the study area as well. Both of these deltas described are composed of recent Holocene sediments, deposited during the current interglacial period. Coleman (1975) classified deltaic systems in more detail, creating six major styles of deltaic sand deposition patterns, and described the Mississippi river delta as being composed of a series of fingerlike thickenings of sands (type I), as opposed to a sheet like pattern (type V), which equates to large gaps in deposition of sands (Fig. 23). Type I distributary sands can be as thick as 360 ft (120 m), which is observed in the Pleistocene deposits of the New Orleans area (Coleman, 1975).

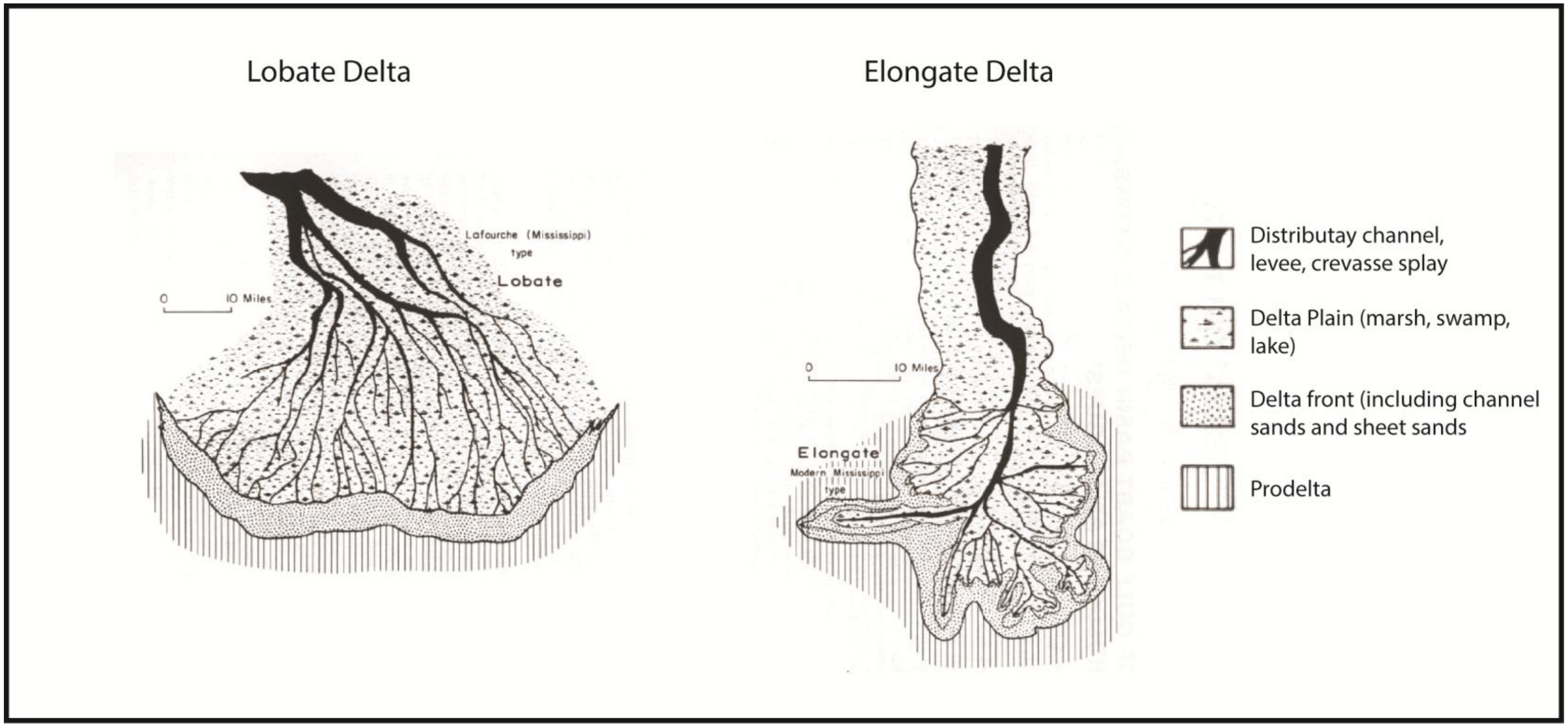

Figure 22. Two styles of delta spatial patterns based on Mississippi River deltas (Modified from Fisher 1969). Note the difference in shape and width of the Lobate versus the Elongate delta.

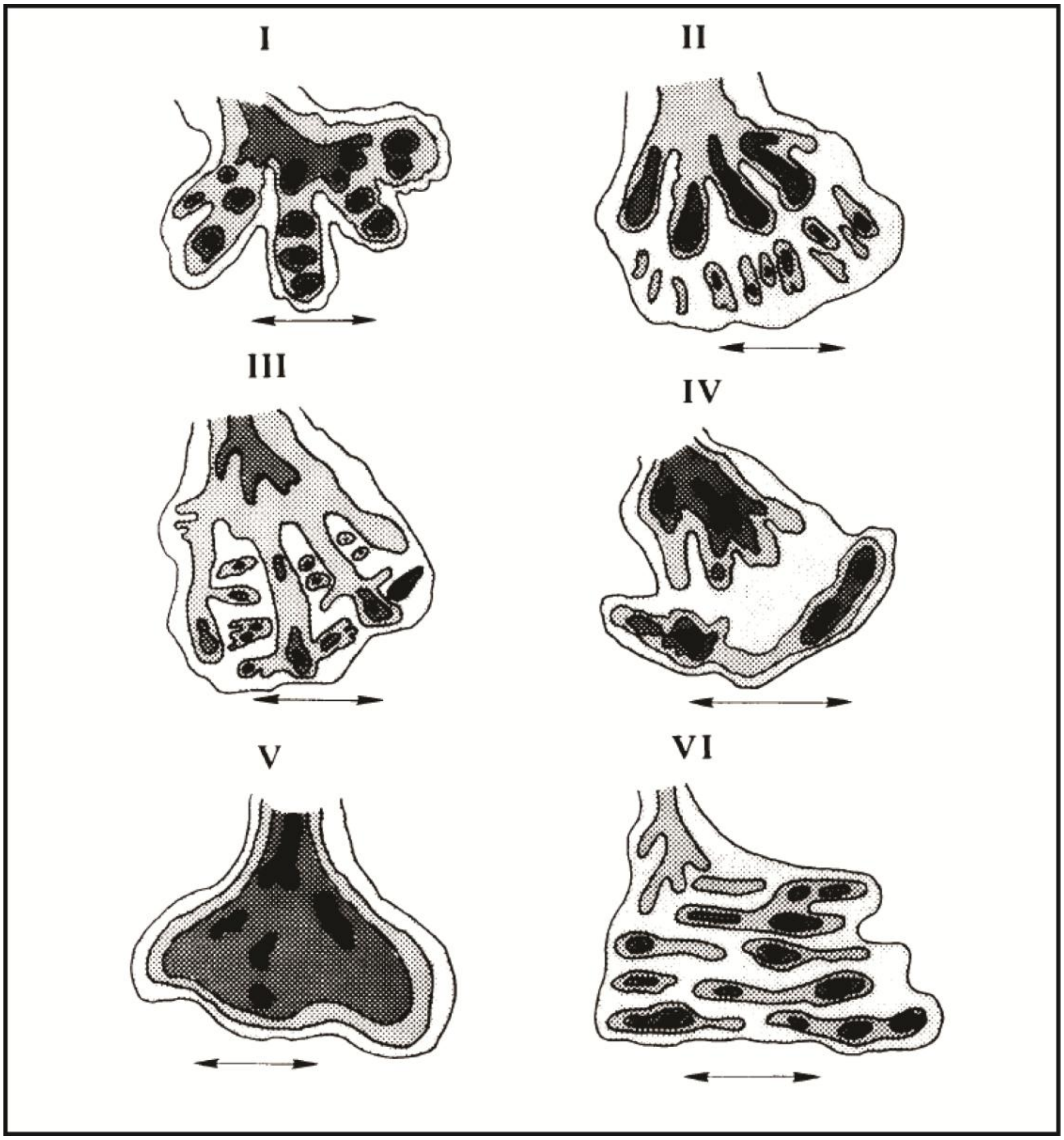

Figure 23. Net sand distribution patterns formed by modern deltas based on factors including wave energy, littoral currents, and tides (Modified from Coleman 1975). Type I corresponds to the modern Mississippi delta.

Relevant depositions sites for the deltaic hypothesis reside at the multiple distributary mouths of the delta, correlating to a flow capable of supporting coarser (sand) sediment transport. Fisher (1969) shows deltaic sands as thick as 100 ft (30 m) in a sequence and up to 300 ft (100 m) thick in a system. These thicknesses match some of the sand thicknesses presented in figures

12 and 13, which show sand thickness in the New Orleans area to range from 10 ft (3 m) to over 250 ft (80 m) thick. The cross sections derived from this study (Figures 12-20) also show a distinct lack of complete horizontal continuity in two dimensions. Many sands become interbedded with clay layers or pinch out over short distances, while other units appear to have some degree of continuity. These changes could be due to the changing locations of the distributary mouths (Fig. 24) as shown by Coleman (1964) , while larger changes in sand continuity may be described by the fingerlike projections (Coleman, 1975). Figure 9 shows the groundwater withdrawal screen thicknesses throughout the study area. The thicknesses vary from 10 feet to over 100 feet, which may reflect positions of thicker sand deposits shown in Figure 23. It should be noted that the pumping wells may not be screened through the full thickness of the aquifer, meaning that Figure 9 cannot accurately define the boundaries of the Gonzales-New Orleans aquifer. However, Figure 9 does show that the aquifer is continuous over much of the study area. If the scale of the type I delta (Fig. 23) is the same as the Lafourche delta (Fig. 22), then there should be zones within the study area where the GZNO pinches out, which log data does not support (Figures 12-20). There is a possibility that the predicted pinch outs are in locations with no data control.

Another factor likely impacting sediment location is the specific orientation of the major deltaic lobes. Orientation of the lobes during the recent sea level highstand show variability, for example, the St. Bernard delta main axis is oriented to the southwest, while the Lafourche lobe points to the south (Fig. 3). As multiple cycles of deltaic lobe migration are possible during an interglacial period, there exists the potential for overlapping deltaic sequences, as observed in the current interglacial with the Teche/Lafourche deltas and the Cocodire/St. Bernard/Plaquemine/Balize deltas (Fig. 3). These overlapping sequences could also explain the

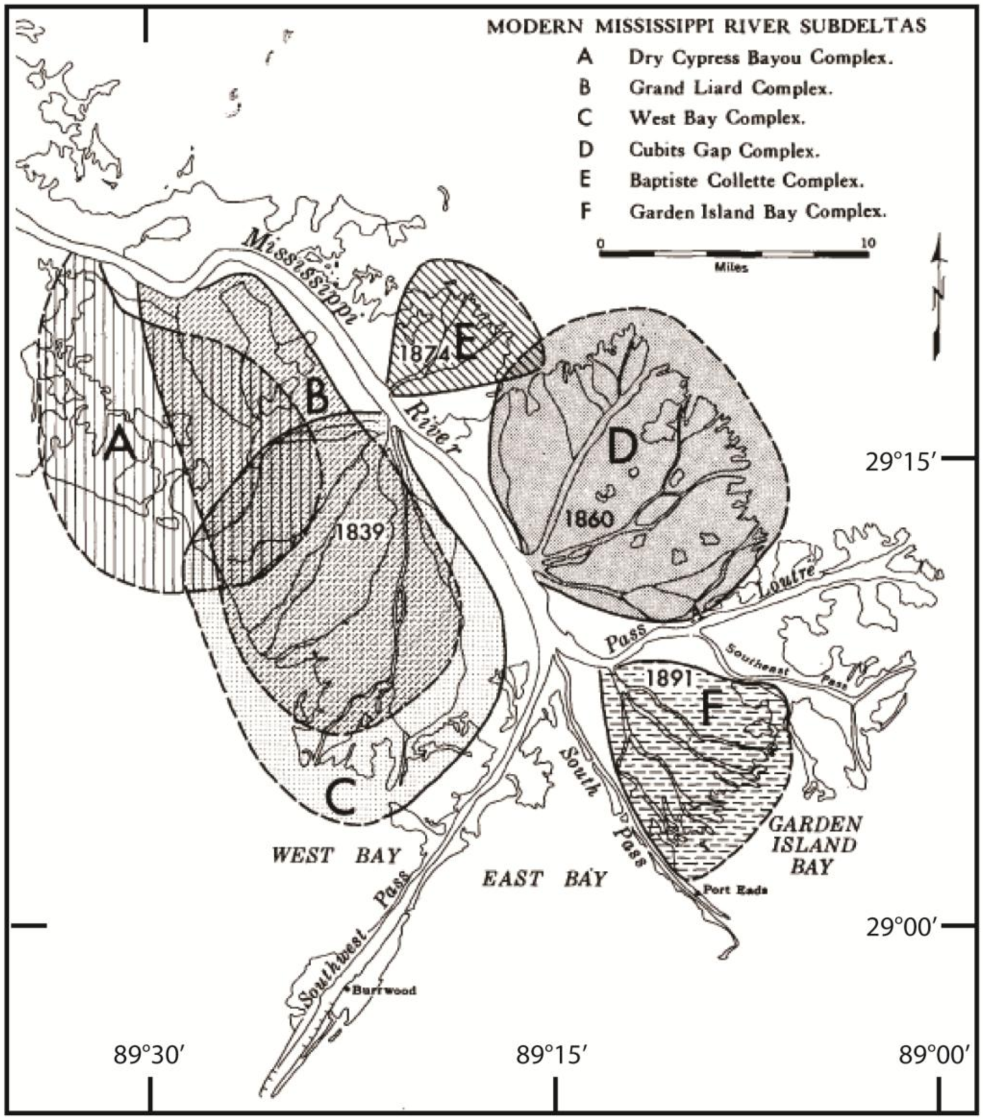

Figure 24. Subdeltas of the Modern Mississippi River delta (Modified from 1964). Note the time of deposition of each subdelta.

lateral changes observed in the study area. For example, in Figure 18, the GZNO segments into three sand units in logs D-8 and D-7. Further east in Figure 18, the GZNO is composed of only one sand unit. The difference could be the result of delta migration, where subdelta migration (Fig. 24), due to distributary avulsion, deposits thin sand beds then a clay layer after avulsion in three successive events. Figure 12 shows the “1200 Foot Sand” aquifer composed of two sand units separated by a thin clay unit in most logs. The scale of the cross section is smaller, but it does support the idea of migrating deposition centers in a presumably short time window.

Another piece of evidence to support the deltaic deposit hypothesis is stated by Morgan (1963). In that study, Morgan came to the conclusion that the aquifers of the New Orleans area initially contained some amount of saltwater and were since flushed by freshwater recharge at outcrop locations. The deltaic system is a zone of mixing between fresh river waters and salty ocean waters of the Gulf of Mexico, meaning some zones of the aquifers could have contained saltier water upon consolidation, while other contained freshwater. However, recent work by Stoessell and Prochaska (2005) has developed an alternative hypothesis for saltwater in the aquifer units. Stoessell and Prochaska (2005) concluded that saltwater in the area is the result of groundwater withdrawal induced lateral migration of salt derived brines emplaced in shallower units via faulting. Thereby attributing saltwater in the aquifers to deeper sources, rather than leftover salty water from incomplete flushing, meaning these aquifers could have contained freshwater initially, which supports a fluvial deposition hypothesis.

While the deltaic deposit hypothesis revolves around cyclic deposition during sea level highstands, the fluvial deposit hypothesis is based on eustatic sea level changes controlling sedimentation rates over longer time scales. At the glacial maximum, sea level is at low-stand, and the ancestral river system was shifted coastward. During the low-stand, erosion occurs creating accommodation space. As ice volume decreases, sea level begins to rise, and these eroded channels are then filled with sediment. Fluvial deposits are composed of several unique facies, which consist of blocky channel fill, crevasse splays, intervening layers of clay and sand, as well as floodplain (Kerr and Jirik, 1990). Migration of the fluvial channel within the study area, accompanied by contemporaneous deposition of previously eroded channels is sufficient to explain the presence of the deposits throughout the study area. This hypothesis has been suggested for sand deposition to the northwest of the study area in the Baton Rouge area by Chamberlain (2012). Changes in channel position could explain the regions where sands appear to thin or pinch out, for example the Norco and Gramercy aquifers in the easternmost section of the study area (Fig. 13). Variations in thickness seen in the cross sections are reasonable based on varying degrees of erosion and subsequent deposition. Because facies changes occur within a fluvial system, the change from one thick sand to several units of sand separated by intervening clays between well logs is plausible and may reflect a change from a blocky channel fill to that of the intervening clay/sand facies.

McFarlan and LeRoy (1988) showed that deposits in southern Louisiana are correlated to changes in sea level, with deposition starting with sea level rise from lowstand and lasting until sea level sea level begins to decrease from highstand. Figure 25 shows a typical depositional cycle for coastal Louisiana during the Pleistocene. Based on the position of the study area relative to the locations of the shifting coastline, it is apparent that the deltaic hypothesis alone does not account for all of the sediment deposition, and that a fluvial component exists. Further evidence is discussed in Griffith (2003), which shows the Gonzales-New Orleans aquifer with an up dip component further north of the study area. It is likely that deltas did not exist this far north based on locations of modern deltas (Fig. 3). Therefore, deposition of the aquifer units further north occurred via fluvial deposition. Based on isopach maps by McFarlan and LeRoy (1988), this fluvial deposition occurred as far south as the locations of lowstand deltas shown in Figure 21. However, Figure 25 also shows that fluvial deposits are overlain by deltaic deposits, meaning that both types of deposits exist within a single sequence.

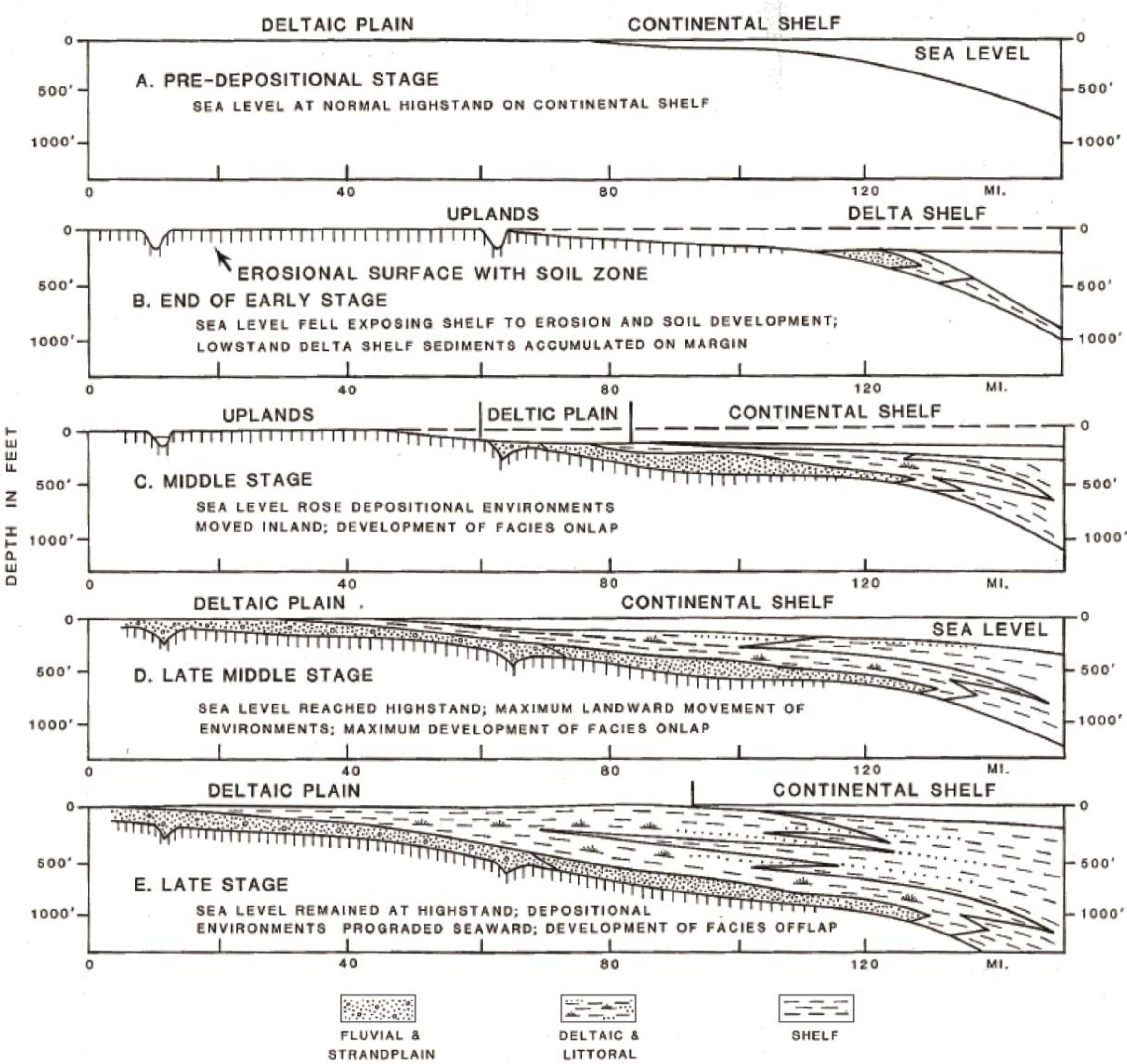

Figure 25. A simplified depositional pattern that occurs during a major Quaternary sea level change cycle in coastal Louisiana (Modified from McFarlan and LeRoy, 1988). Note the overlap between fluvial and deltaic sediments.

The study area likely experienced both types of sedimentation depending on the interplay between allogenic and autogenic forces. These sediments are thought to be up to three million years old, spanning the entire Pleistocene epoch, and therefore have experienced multiple transgressions and regressions of the coastline (McFarlan and LeRoy, 1988). Many channel/delta migrations are also possible in this time frame. There are numerous scenarios involving fluvial and deltaic deposition that are possible to characterize the subsurface geology below the New Orleans area. Both the fluvial and the deltaic hypotheses show that the complexity shown in the subsurface architecture is geologically reasonable. However, the exact pattern of the deposition within the study area is not fully resolved due to the spacing of geophysical well logs relative to the scale of changes within a fluvial/deltaic system, creating uncertainty in subsurface architecture.

4.3 Subsurface Heterogeneity Effects on Numerical Modeling

The cross sections developed for this study clearly show a high degree of heterogeneity that must be accounted for in future studies done in this area. The next step would be to develop a numerical groundwater model to study flow and solute transport resulting from groundwater pumping of the aquifer units. These cross sections represent a conceptual model that must be discretized in three dimensions for use in a computer simulation. As there was little geologic evidence with which to correlate tops and bottoms of sandy units, as well as a high degree of heterogeneity between geophysical logs, the cross section interpretation was kept simple. It is likely that there is an even higher amount of heterogeneity that is not captured in the cross sections, as evidenced in Figure 12. However, simplifying the geology further for the purpose of remediation modeling is not recommended. Several studies (Rojas et al., 2006; Feyen et al., 2008) have recently looked into the uncertainty of conceptual models as a main source of error in groundwater modeling results. The last few decades have seen a push to develop methods that are capable of optimizing model parameters, which has resulted in numerous inversion techniques (Carrera et al., 2005). However, these calibration approaches focus only on simulation parameter values, ignoring the impacts of incorrect model structure and input measurement data

(Rojas et al. 2006). Many authors (Rojas et al., 2006; Feyen et al., 2008; Tsai, 2010) have discussed the current issues with conceptual model uncertainty and summarized the main issues with the current approaches. One issue is that data can fit multiple conceptual models equally well, creating the next issue of calibration not being capable of verification of a conceptual model. As groundwater remediation and management models are based on conceptual geologic models, large uncertainty is present in systems that are highly heterogeneous. Unexpected failure of remediation methods may result from the use of a single conceptual model coupled with only one parameter estimation method, as these techniques underestimate model uncertainty (Tsai, 2010).

The cross section interpretations shown here represent only one of the potential subsurface realizations. One parameter that created uncertainty in the cross sections produced is dip. Because there were very few marker beds, it was difficult to make an estimate of dip, especially one that could be applied to the entire section. Figure 13 runs from north to south, but this may not be a direction of maximum dip, due to the variability in fluvial/deltaic axis direction. The variability of dip could represent a large error in these interpretations. Incorporation of different values of dip will cause some changes to the connectivity of sands at the midpoint between logs. Another source of uncertainty is created by the tabular shape used for lateral extension of sand bodies between logs. Such a simple shape likely underestimates sand thickness in certain areas and overestimates in others. Different values in dip and/or the use of different sand body shapes can increase or decrease the connected sand thickness at points between well logs as well as disconnect sand bodies. This change in sand connection affects the flux of water through the system. In the cross sectional view of this study, the flux can be thought of in terms of transmissivity, which is the volume of water flowing through a cross sectional area

(Transmissivity = Permeability*Thickness). Therefore, an increase in sand connection corresponds to an increase in transmissivity, which means an increase in solute transport flux. The decision on whether to include factors such as dip or sand body shape greatly influences the manner in which groundwater flow and solute transport occur. As this introduces large variability into predictions of future saltwater encroachment, it is important to consider multiple subsurface realizations in future groundwater management as the subsurface architecture controls the movement of water through the system.

4.4 Impacts on Solute Transport Pathways

Figure 13 represents a cross section that cuts through the current drawdown cone in water levels (in the GZNO) caused by heavy pumping in the New Orleans industrial district. The cone is large in size and its extent covers the entire study area (Fig. 6). The difference in water levels at points in the center of the cone from the western side of the study area is approximately 110 ft (35 m), representing a significant drawdown issue. Figure 2 shows chloride concentrations in mg/L at locations within the study area. It is apparent that the saltiest water lies within the southern reaches of the study area, at concentrations up to 4000 mg/L. Chloride concentration decreases moving from south to north, creating a freshwater area within the interior of the study area.

Figure 13 is located directly in the center of the drawdown cone, with logs S-3, S-4 and S-5 directly at the presumed center of the cone. The aquifer is thick in this area, with those logs showing thickness up to 200 ft (70 m). North of well log S-5, there exists connectivity between sands, however, the southern portion of the cross section does not show lateral connection between units. Thick clay units are observed in the southernmost logs above depths of 1000 ft

(300 m). Up dip movement of saltier water from the south, shown in Figure 2, does not seem feasible along this cross section. Unfortunately, there are few to no geophysical well logs to the immediate east of Figure 13, making it difficult to assess aquifer connectivity in this direction. Figure 17 (to the west) shows a connected sand unit correlating to the Gonzales-New Orleans aquifer system, but there is disconnection in the sand unit between logs D-5 and D-6. However, sand units are connected between D-6 and D-9, providing evidence that there are pathways for solute transport to the west. Figure 20 shows that sands are connected from east to west in the region between transects D-D’ and E-E’, meaning solutes can move in this direction as well. Because the source of the saltwater is not well constrained outside of the study area, it is difficult to determine if these are viable transport directions, though cross sections do show that the sand geometry can support this motion. These units likely have some form of continuity in three dimensions that cannot be determined from this study, meaning other pathways are plausible.

5. CONCLUSIONS

The research performed in this study has determined that the subsurface architecture in the New Orleans area units is complex. The complexity in the subsurface is explainable by the combination of deltaic and fluvial sedimentation that has persisted at the Mississippi River and Gulf of Mexico interface. Based on modern analogs of the Mississippi River delta, it is possible to discuss scenarios that can characterize the heterogeneity observed. These scenarios range from shifting subdeltas to overlapping deltaic bodies to fluvial migrations, creating a great number of possibilities for sedimentation patterns. Different units appear to show different levels of connectivity in the study area, which could be due to different combinations of the scenarios discussed above. For example, the USGS Gonzales-New Orleans aquifer appears to be the only unit to preserve a consistent vertical thickness and horizontal connectivity at small scales (Fig. 12). The unit appears continuous throughout the study area, which does not appear to be the case for shallower units.

Sands are observed to thin dramatically over short distances of 1000 ft (300 m). The spacing of data points in the area is generally much larger than 1000 ft (300 m), meaning that many of the changes observed to occur over short distances cannot be determined in the stratigraphic record. This creates a challenge in creating a deterministic geologic model for use in numerical modeling of groundwater flow and solute transport. The potential differences created by multiple subsurface architecture realizations of the subsurface are capable of having large impacts on the pathways and velocity for solute transport. Interpretation shows some disconnection of sand units in the south of the study area, but there are other avenues for solute transport separate from Figure 13. Other interpretation techniques utilizing different dip values or different sand body shapes may reveal different conclusions. Further, this study was not able to distinguish these units in three dimensions, creating large gaps of data in between cross sections. The three dimensional connectivity of these units will have a direct impact on the distribution of saltwater.

The combination of large distances between geophysical well logs as well as the complexity of fluvial/deltaic deposition creates a highly heterogeneous subsurface architecture that is not fully explained by the results of this study. The overall subsurface heterogeneity demonstrates the need for multiple realizations of the subsurface architecture that are capable of estimating model uncertainty in order to address saltwater encroachment via numerical models involving groundwater flow and solute transport in the New Orleans area.

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APPENDIX: WELL LOG INFORMATION

Table A. Information on well logs used for this study. Permanent datum calculated by removing effects of ground elevation, Kelly Bushing height, etc. * Denotes no information in log header regarding elevation of logging apparatus, in these cases the datum is assumed based on average values from other oil wells.

Well Designation in this Study	Well Use in this Study	Well Name	Latitude (N)	Longitude (E)	Date of Last Logging Run	Depth Interval (ft)	Log Elevation above Perm. Datum (ft)	Source
A1	A-A', G-G'	60323	30.07210	-90.29648	5/4/1956	128 - 11000	32	SONRIS
A2	A-A'	41680	30.05827	-90.29338	10/19/1950	119 - 10060	17*	SONRIS
A3	A-A'	Jf-183	30.03500	-90.27528	NA	16 - 750	-12.2	USGS
A4	A-A'	Jf-187	30.01159	-90.27841	7/24/1986	40 - 800	-9.7	USGS
A5	A-A'	Jf-217G	30.00000	-90.27806	6/27/2007	10 - 740	5.9	USGS
A6	A-A'	59524	29.97860	-90.29418	1/24/1956	216 - 11020	22.1	SONRIS
A7	A-A'	970880	29.95538	-90.26907	5/20/1965	110 - 2720	18.05	SONRIS
A8	A-A', H-H'	66030	29.91021	-90.27258	10/17/1957	175 - 13600	14.7*	SONRIS
A9	A-A', F-F'	58976	29.84811	-90.23828	1/17/1956	211 - 12338	19.8	SONRIS
B1	B-B'	125459	30.15200	-90.21618	9/3/1968	520 - 11300	30.65*	SONRIS
B2	B-B'	64043	30.09450	-90.21008	1/3/1957	200 - 9250	7	SONRIS
B3	B-B'	64629	30.08410	-90.20978	2/3/1957	252 - 7600	18.6	SONRIS
B4	B-B'	Jf-186	30.03972	-90.24611	NA	26 - 746	-8.7	USGS
B5	B-B'	52513	30.01160	-90.23108	7/31/1954	120 - 10006	13.7	SONRIS
B6	B-B'	Jf-184	29.99056	-90.24222	NA	40 - 860	1.6	USGS
B7	B-B'	Jf-185	29.97306	-90.21000	NA	20 - 850	-5	USGS
B8	B-B', I-I'	56237	29.92730	-90.19968	6/20/1955	364 - 9451	35.8	SONRIS
B9	B-B', I-I'	42158	29.91100	-90.20828	12/22/1950	152 - 9658	20.7	SONRIS
B10	B-B', H-H', I-I'	44054	29.89081	-90.21278	3/27/1952	141 - 12700	17.9	SONRIS
C1	C-C', G-G'	31165	30.04340	-90.14688	5/2/1946	190 - 10897	16.6	SONRIS

Table A. Continued.

C2	C-C’	Jf-175	30.01944	-90.14444	11/9/1983	14 - 716	-2	USGS
C3	C-C’	Jf-120 G	29.96667	-90.14667	1/24/1961	68 - 780	12.9	USGS
C4	C-C’	Jf-211	29.94833	-90.14639	11/1/2004	10 - 860	17.9	USGS
C5	C-C’	Jf-43 G	29.93333	-90.14694	1/24/1961	80 - 822	24.58*	USGS
C6	C-C’	Jf-21 G	29.91667	-90.14611	5/26/1959	80 - 801	10.8	USGS
C7	C-C’, H-H’	Jf-130 G	29.90000	-90.13944	2/1/1962	10 - 616	1.7	USGS
C8	C-C’	Jf-212 G	29.88333	-90.15778	4/26/2004	10 - 760	0.3	USGS
C9	C-C’, F-F’	165879	29.83882	-90.16827	11/5/1979	200 - 10300	22.5	SONRIS
D1	D-D’, G-G’	Or-214	30.02806	-90.07000	8/3/1984	40 - 804	6.3*	USGS
D2	D-D’	Or-47 G	30.01667	-90.06778	5/18/1961	48 - 496	-5.9	USGS
D3	D-D’	Or-192 G	29.99965	-90.06757	7/16/1975	20 - 730	-1.2	USGS
D4	D-D’	Or-54 G	29.95000	-90.06250	12/11/1959	100 - 756	27.2	USGS
D5	D-D’	Or-50 G	29.93333	-90.05417	6/16/1960	126 - 717	36.1	USGS
D6	D-D’	Jf-181	29.90944	-90.05306	10/17/1984	90 - 830	2.6*	USGS
D7	D-D’, H-H’	Jf-166	29.89861	-90.07833	12/10/1981	22 - 1360	6.8	USGS
D8	D-D’, H-H’	Jf-215 G	29.88333	-90.09444	7/14/2006	14 - 850	1.5	USGS
D9	D-D’, F-F’	79407	29.82720	-90.08778	5/30/1960	204 - 10700	19.7	SONRIS
E1	E-E’	Or-176	30.16306	-89.87028	3/24/1964	170 - 3000	25	USGS
E2	E-E’	150661	30.09650	-89.86677	2/5/1976	110 - 10010	22	SONRIS
E3	E-E’, G-G’	47277	30.05070	-89.90317	3/20/1953	313 - 12952	10.9	SONRIS
E4	E-E’	970918	30.02270	-89.91257	7/30/1963	200 - 6640	14.2	SONRIS
E5	E-E’	146563	29.99810	-89.93677	11/20/1974	205 - 9540	23.72	SONRIS
E6	E-E’	Sb-34	29.93361	-89.97222	7/3/1963	90 - 790	20.4	USGS
E7	E-E’, H-H’	38761	29.90440	-89.99977	10/1/1969	180 - 10418	13.4	SONRIS
E8	E-E’	101223	29.88490	-89.99877	3/16/1964	199 - 10520	15.4	SONRIS
E9	E-E’, F-F’	128784	29.81931	-90.01697	8/17/1969	180 - 12740	15.8	SONRIS
W1	I-I’	43530	29.90791	-90.20958	8/20/1951	164 - 9654	17.5	SONRIS
W2	I-I’	49046	29.91490	-90.20768	8/8/1953	160 - 9800	24.1*	SONRIS

Table A. Continued.

W3	I-I’	54050	29.93180	-90.19328	11/18/1954	334 - 9450	32.7	SONRIS
X1	F-F’	50806	29.81151	-89.98867	2/24/1954	213 - 11306	19.4	SONRIS
X2	F-F’	57885	29.82361	-89.96627	11/30/1955	160 - 12812	23.1	SONRIS
X3	F-F’	71898	29.81361	-89.91307	9/11/1958	110 - 1860	21.3	SONRIS
Y1	G-G’	61199	30.08400	-90.20168	6/21/1956	508 - 10003	23	SONRIS
Y2	G-G’	31164	30.06190	-89.98487	7/11/1946	248 - 11075	16.6	SONRIS
Y3	G-G’	Or-201	30.05861	-89.95500	8/7/1981	40 - 810	-4.3	USGS
Z1	H-H’	38689	29.90860	-90.19278	10/25/1949	152 - 9544	17*	SONRIS
Z2	H-H’	Jf-193	29.89889	-90.15417	4/6/1988	26 - 520	1.3	USGS

VITA

James E. Ayrer IV was born in 1988, in Montoursville, Pennsylvania. He graduated from Montoursville Area High School in May 2006. In 2010, he graduated from The Pennsylvania State University with a Bachelors of Science in Geosciences. In spring of 2012, he began his studies at Louisiana State University, when he also began work at the U.S. Geological Survey. James will graduate with a Master of Science in Geology in August, 2013.